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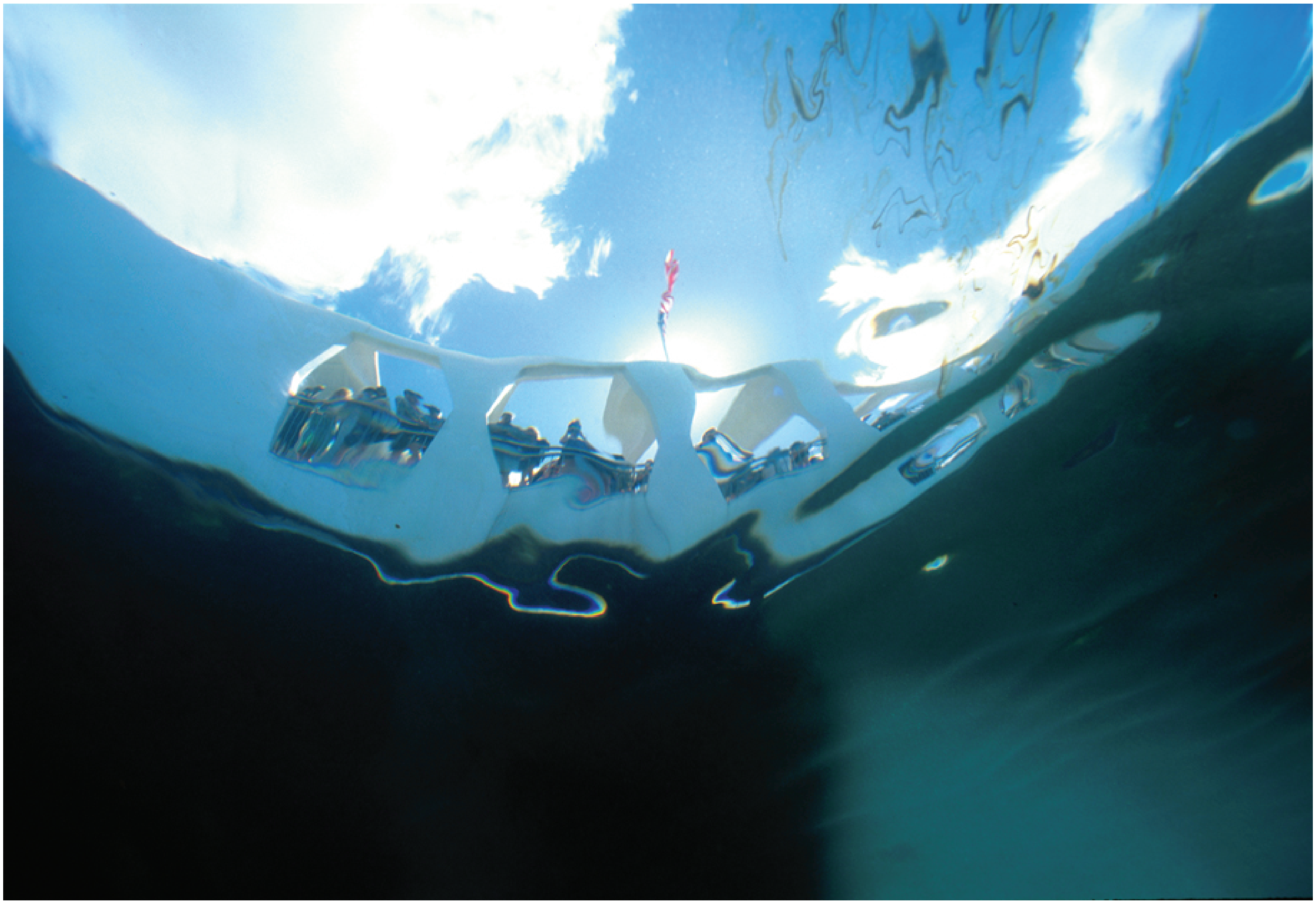

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Long-Term Management Strategies for USS *Arizona*, A Submerged Cultural Resource in Pearl Harbor

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PREFACE

This report represents the final product in partial fulfillment of Department of Defense Legacy Resources Management Fund Projects Nos. 02-170, 03-170, 04-170, and 05-170, which were funded in Fiscal Years 2002–2005. Requested funding was provided in 2002, while only part of requested funding was provided in the other years. Because of incomplete funding, some tasks were reduced or eliminated. This report fulfills the Legacy Project report requirements. Legacy funding was augmented with funding from other sources, principal among these are the National Park Service (NPS) Systemwide Archeological Inventory Program, USS *Arizona* Memorial, *Arizona* Memorial Museum Association, the NPS Submerged Resources Center, and significant in-kind support from the federal agencies and academic institutions that have contributed to this report. Although this is the final report for the Legacy Project, it constitutes an interim synthesis report for the USS *Arizona* Preservation Project, which remains ongoing.

The project's primary focus was to acquire requisite data for understanding and characterizing the complex corrosion and deterioration processes affecting *Arizona*'s hull, both internally and externally, and to model and predict the nature and rate of structural changes resulting from corrosion. The interdisciplinary research approach to characterizing and understanding USS *Arizona* deterioration and integration into a predictive model reported here was designed to produce cumulative data whose synthesis will inform management actions regarding long-term stewardship of this National Historic Landmark site. Beyond informing management decisions about *Arizona*, we believe this research approach has produced results that contribute to each of the disciplines involved, and which are directly applicable to the thousands of steel legacy vessels submerged worldwide. This report represents what we have learned so far about USS *Arizona* and other submerged steel hull's deterioration. Because *Arizona* research is not complete, and data derived from the monitoring program have not been generated and incorporated, report conclusions will be refined and may change as data-gaps are filled and new information is added. Data presented here represents the most informed view of the ship based on scientific observations, investigations and experimentation by outstanding experts in numerous fields, but it is necessarily incomplete because not all research domains have been completed. We have learned a great deal that will allow NPS and U.S. Navy managers to make correct decisions about immediate needs within a stewardship framework, although lack of complete funding has resulted in gaps in our knowledge about critical aspects of *Arizona*'s deterioration. In that regard, the work reported here is an important step toward refining questions that guide future research directed toward a full understanding of *Arizona*'s deterioration.

CHAPTER 1

Introduction

Larry E. Murphy and Matthew A. Russell

SIGNIFICANCE

USS *Arizona*, a National Historic Landmark—the highest level of national historic significance in the United States—is a U.S. Navy object administered cooperatively by the National Park Service (NPS) and U.S. Navy, and among the most recognized and visited war memorials in the United States (Figure 1.1). A million and a half visitors annually make the short trip across Pearl Harbor to the USS *Arizona* Memorial, which spans the sunken hull. The Memorial is located off the northwest corner of Ford Island in the East Loch of Pearl Harbor, South-central Oahu, Hawaii (Figure 1.2).

The *Pennsylvania*-class battleship USS *Arizona* was completed in 1916 (Figure 1.3) and was sunk in Pearl Harbor, Hawaii on December 7, 1941 during the Japanese attack on the U.S. Navy's Pacific Fleet. In the first 15 minutes of the attack, Japanese aircraft struck *Arizona* with several bombs, strafed the ship, and then at about 0810 delivered the battleship a mortal blow. A Japanese Nakajima B5N2 "Kate" horizontal bomber dropped a single 1,760-pound projectile constructed from a 16-inch armor piercing shell that struck near Turret No. 2 and penetrated deep into the battleship's interior before exploding and sympathetically detonating the black powder magazine, which ignited the forward magazines containing smokeless powder for the forward turrets (Figure 1.4). When the forward magazine exploded, it destroyed most of the battleship's forward half below the upper deck, presumably including the forward oil bunkers aft to approximately frame 78. The two forward turrets and the conning tower dropped about 20 feet, their foundations destroyed by the blast. The ship sank in minutes, and the explosion ignited fires that raged for two-and-a-half days (Figure 1.5). The explosion and subsequent conflagration killed 1,177 sailors and marines aboard USS *Arizona*—the event remains the largest single-ship loss of life in U.S. naval history. More than 900 men remain entombed within the ship and are considered buried at sea with the battleship as their final resting place. Millions of visitors, many international, consider the vessel a national icon. This naval memorial remains deeply ingrained in American consciousness, and still commands an honor guard from the many capital ships that ply Pearl Harbor today (Figure 1.6).

USS *ARIZONA* PRESERVATION PROJECT

Beginning in 1998, the NPS Submerged Resources Center (SRC) and USS *Arizona* Memorial (USAR), along with many partners, conducted a comprehensive research program

Figure 1.1. The USS *Arizona* Memorial (NPS Photo by Brett Seymour).

directed at understanding the nature and rate of a range of natural processes affecting USS *Arizona*'s deterioration. The USS *Arizona* Preservation Project is a multi-year, interdisciplinary and cumulative effort, with each element of the project contributing to basic research required to make informed management decisions for *Arizona*'s long-term preservation and to minimize environmental hazard from a potential fuel oil release of the estimated 500,000 gallons still onboard the battleship (Russell, et al. 2004). Developing reasonable and effective management alternatives and determining the most desirable actions, particularly those regarding intervention or rehabilitation, cannot be done without a sound, scientifically-based research program conducted within a management framework aimed at collecting data necessary to make informed management decisions. Because of the particular national importance of *Arizona,* any research, as well as any solution to the oil issue, must incorporate a minimum-impact approach, consistent

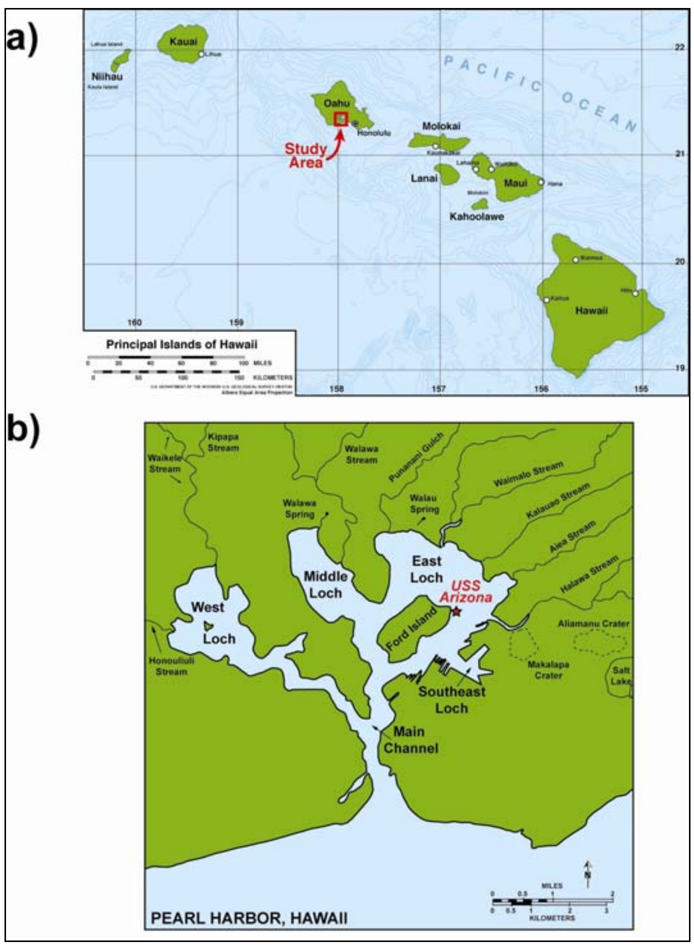

Figure 1.2. Map of the study area. a) Location of Pearl Harbor in relation to the main Hawaiian Island chain; b) Location of the USS *Arizona* Memorial in Pearl Harbor relative to Ford Island (Graphic courtesy of U.S. Geological Survey).

Figure 1.3. The USS *Arizona* in the East River in New York City after launching in 1916 (USS *Arizona* Memorial Photo Archives).

Figure 1.4. USS *Arizona* exploding on December 7, 1941 (USS *Arizona* Memorial Photo Archives).

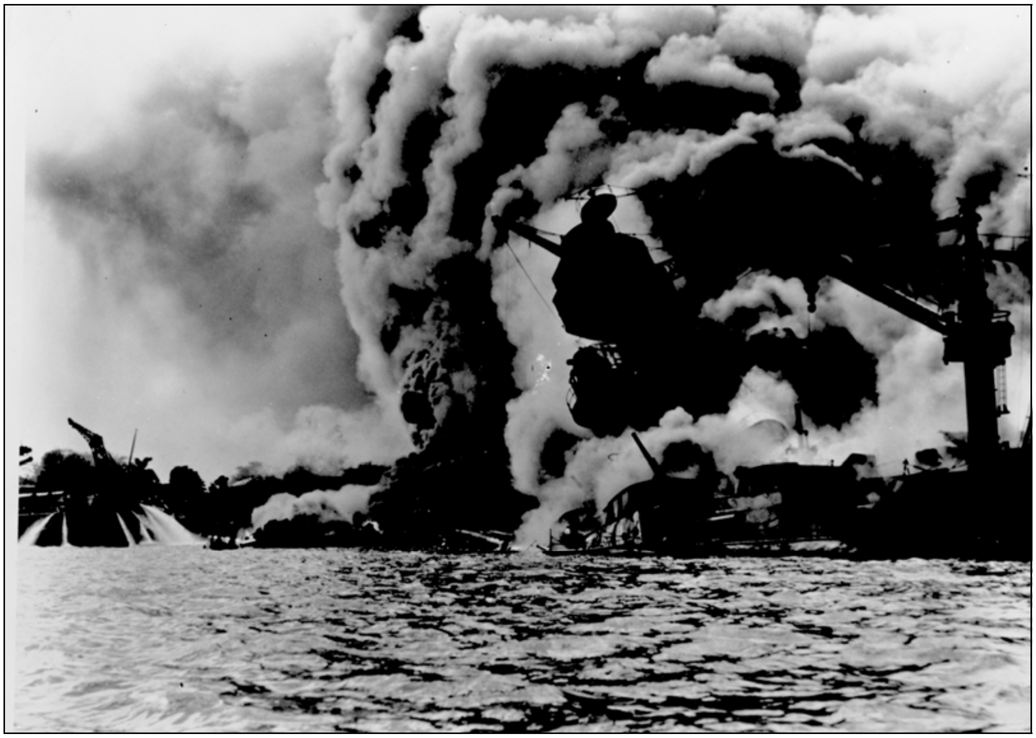

Figure 1.5. USS *Arizona* burning after the Pearl Harbor attack (USS *Arizona* Memorial Photo Archives).

Figure 1.6. USS *Abraham Lincoln*'s officers and crew honoring USS *Arizona*, 2004 (USS *Arizona* Memorial).

with standard NPS policy (Russell and Murphy 1997), but with added respect due the ship as a tomb, or long-term preservation of the ship may be compromised. Unnecessary disturbance to *Arizona*'s hull is likely to be seen by many as more problematic than the limited oil release now occurring, although managers will ultimately have to face the possibility of a large release Bunker C fuel oil. Addressing the oil release problem within a site-preservation framework incorporated in this project provides the best balance of competing social values, and it has the highest probability of success for arriving at the best and most defensible solution for both issues while providing maximum preservation and protection.

In addition to the particular issues surrounding the battleship itself, project principals designed the USS *Arizona* Preservation Project to serve as a model for intervention actions directed at other historic vessels leaking contaminants into the environment, and to produce results directly applicable to preservation and management of historical iron and steel vessels worldwide (Jeffery 2004). Although the project focused on management concerns and collecting physical data necessary to make informed management decisions regarding USS *Arizona*, we planned and conducted the research project within an archeological framework and in the broader context of the archaeology of the Pearl Harbor attack (Delgado 1992; Gould 2000; Lenihan 1989b; Rodgers, et al. 1998).

This chapter highlights previous research conducted on the site and outlines the origin of the current management-based research program on USS *Arizona*. It begins by reviewing the rationale that led to the genesis of the USS *Arizona* Documentation Project in the early 1980s, and then traces the changing management needs to the present day and addresses the question of oil removal. The chapter next details the interdisciplinary nature of the current project and the complex interactions of federal, state, and private partners involved. Finally, it discusses the organization of the rest of this volume.

PROJECT BACKGROUND AND RATIONALE

Previous Research

NPS preservation efforts on USS *Arizona* began when the first superintendent of the USS *Arizona* Memorial asked SRC to document the ship. This request resulted in a five-year project from 1983–1988 designed to address specific concerns from NPS managers responsible for the historic battleship and memorial (Lenihan 1989b). In late 1980, the U.S. Congress created the USS *Arizona* Memorial as a unit of the National Park system and charged the new superintendent with two fundamental concerns: interpretation and management (Cummins and Dickinson 1989:158). When the NPS took over the Memorial's operation from the Navy, the agency found it faced a nearly insatiable public curiosity about the Pearl Harbor attack overall, and USS *Arizona* specifically, and found it lacked answers to some very basic questions. Because tantalizingly little of *Arizona* is visible above the waterline, and all depictions of the ship were either of it on the surface or during the attack, the most often-asked question was some variation of "what does the ship look like now?" In addition, although official Navy records attribute the damage and eventual sinking of the battleship to aerial bombs, there were eyewitnesses who insist they saw *Arizona* struck by at least one torpedo and saw a bomb penetrate the ship's smoke stack. Varying historical accounts about the events of December 7, 1941 and the aftermath contributed to a general confusion about what really happened. More than 40 years after *Arizona*'s sinking, fundamental questions lingered—questions that could potentially be answered by archeological investigation of the material remains *in situ* on the harbor bottom (Lenihan 1989a).

In addition to public interpretation, the NPS's other priority is resource management and historic preservation. Before the NPS began managing *Arizona* there was little concern for the vessel's preservation by the Navy, although memorialization efforts began soon after the war and led to construction of the present memorial in 1962. With the Navy retaining ownership and NPS mandated to actively manage the site beginning in 1981, however, such basic questions as "what condition is the wreck in?" and "how quickly is it deteriorating?" needed to be addressed before the agency could make effective management decisions about how to treat the vessel's remains. Because *Arizona* is the final resting place for more than 900 sailors and marines, a significant management question becomes whether the site should be left alone to deteriorate naturally or whether the agency intervene to preserve the integrity of the tomb (Cummins and Dickinson 1989:163-164). Although at the time the NPS, nor anyone else, had experience actively managing sunken steel vessels, it did have considerable experience with standing remains on archaeological sites and with historic structures. With this background, from the beginning of its management tenure, the NPS treated *Arizona* as a structural archaeological site and used archaeological methodology to provide answers to the agency's questions, regarding both site interpretation and management. In response to the practical needs of site managers, the two basic questions NPS archaeologists were asked by the Memorial superintendents during the 1983–1988 project became "what's there?" and, then, "what's happening to what's there?" (Lenihan 1989a).

NPS researchers effectively answered the first question in 1984 by documenting the hull and producing of a series of detailed drawings, basically an archeological site map, based upon thousands of direct measurements (Lenihan and Murphy 1989:83-86)(Figure 1.7). Not only are these images a powerful tool for public interpretation and understanding, they are also the foundation for all additional work on the ship. From these archaeological drawings and additional detail, a scale model was created for the Memorial visitor center to allow visitors to visualize that once on the Memorial, they were standing directly over the remains of the battleship—it connected the few features visible above the water to the ship below (Figure 1.8). The drawings and model directly contribute to an interpretive scheme that highlights the reverential aspects of the site and presents enough information to visitors to allow them understand the site and "to construct their own meaning of the site while partaking in the general atmosphere of subdued restraint and poignancy" (Kelly 1996:56).

The second question, "what's happening to what's there," is essentially directed at determining the nature and rate of corrosion affecting *Arizona*'s steel hull, and is an extremely complex and multifaceted question that could not be easily answered. Researchers in the 1980s addressed *in situ* corrosion of a submerged iron or steel shipwreck by collecting baseline data, including corrosion potential (E_{corr}) of the steel hull using a bathycorrometer, essentially a sea water equivalent silver/silver chloride (Ag/AgCl) reference electrode—a critical data set for evaluating corrosion rate and by examining the concretion and biological organisms attached to the exterior hull (Henderson 1989, see also Chapter 5). At the same time, the first two Memorial superintendents laid out a series of future research objectives based on serious management concerns—objectives that would guide the next phase of research that began in 1998 and that is reported on in this volume (Cummins and Dickinson 1989:167-168). Cummins's and Dickinson's research questions provided the management framework for the USS *Arizona* Preservation Project.

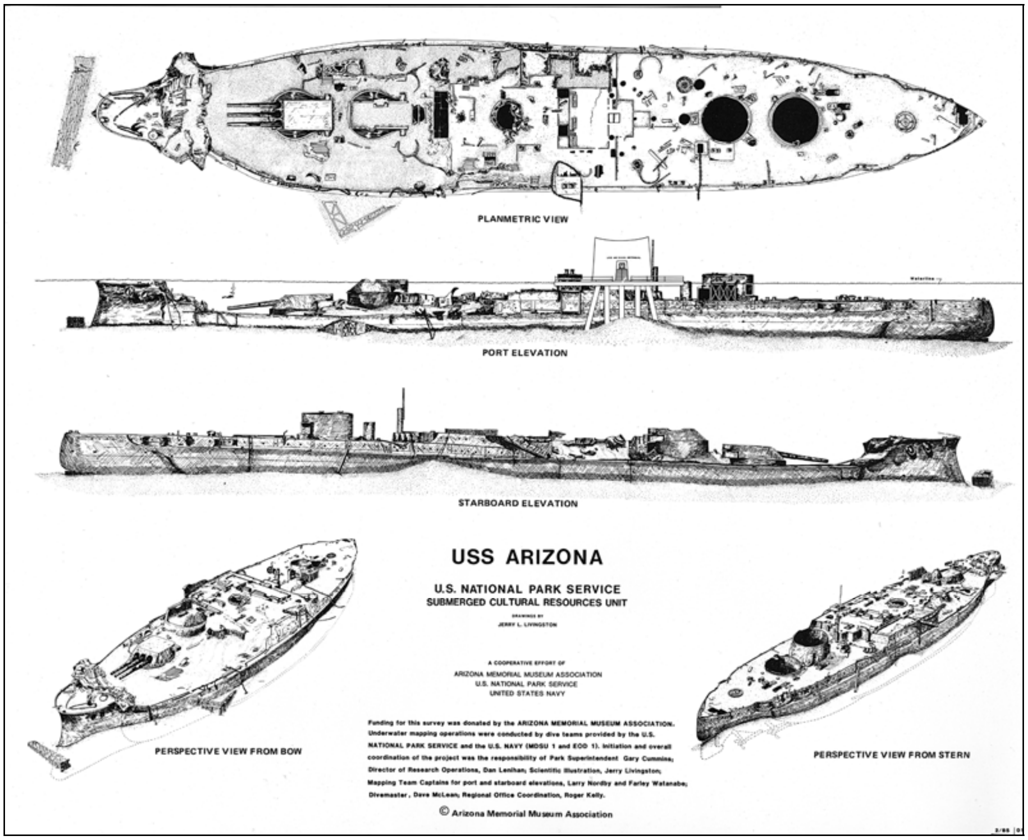

Figure 1.7. Scale drawings of USS *Arizona* (Drawing by NPS-SRC, 1984).

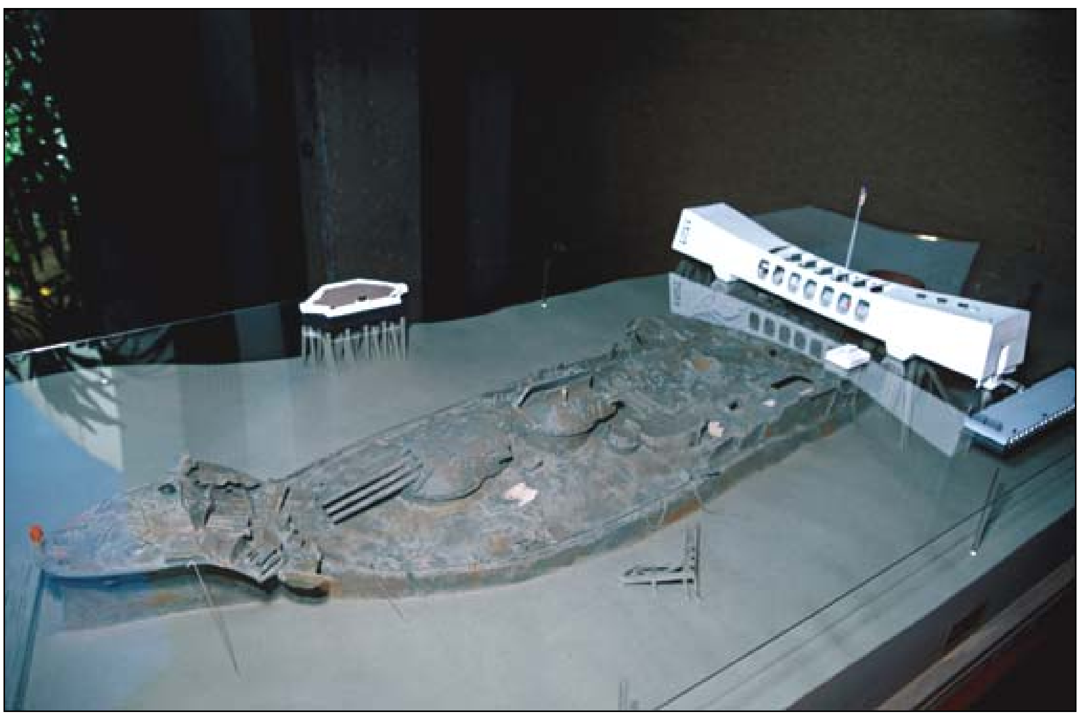

Figure 1.8. Scale model of USS *Arizona* produced from archeological scale drawings (NPS Photo by Brett Seymour)

Current Project Genesis

Corrosion data collected in the 1980s and management needs for effective NPS stewardship suggested that future research should focus on four key areas. First, conduct direct analysis of steel hull samples to determine corrosion rate variability across *Arizona*'s hull fabric. Second, determine the nature and exact mechanism of electrochemical corrosion in order to predict corrosion rates in areas not directly sampled or inaccessible to researchers, and develop a non-destructive methodology to test the predictive corrosion model. Third, using original engineering plans and corrosion data, create a computer-based model to predict the hull's current lifespan if there is no intervention. And fourth, create a long-term management plan including environmental and structural monitoring of *Arizona*'s hull (Cummins and Dickinson 1989:167-168). Although these goals were outlined in 1989, change in management at the USS *Arizona* Memorial resulted in change in management priorities, and no systematic research was conducted nor any attempt to implement the 1989 research recommendations were undertaken until the late 1990s. Kathy Billings became superintendent of the USS *Arizona* Memorial in 1996 and immediately re-focused attention on earlier management goals and objectives, and in 1998, SRC was tasked with implementing the 1989 research strategy. SRC researchers quickly partnered with a variety of outside collaborators to leverage the limited available funding, but also realized a more secure funding base would be necessary to fully implement the comprehensive research program necessary to address management questions.

Often overshadowing larger preservation issues is concern about the estimated 500,000 gallons of oil still contained within *Arizona*'s bunkers. The oil currently bubbles out of the ship one small drop at a time, each shaped like a marble-sized black pearl, totaling about 9–10 quarts a day. Although *Arizona* has been leaking oil steadily since 1941, intense media attention surrounding the Pearl Harbor attack's 60th anniversary in 2001, including three major television documentaries by National Geographic, Discovery Channel and History Channel, an article in National Geographic magazine (Vesilind 2001), and Disney's epic World War II blockbuster *Pearl Harbor* focused public attention on the half-million gallons of oil remaining in *Arizona*'s corroding hull, which was unanimously described as a pending environmental calamity. Based on media characterizations, the U.S. Navy began putting out feelers about the possibility of oil removal. During preliminary discussions with U.S. Navy personnel in Pearl Harbor, NPS representatives suggested that before hasty, and possibly destructive, measures were taken to mitigate the potential environmental hazard, a comprehensive assessment of *Arizona*'s hull should be undertaken to determine a curve of deterioration and pinpoint exactly where the battleship currently falls on the curve (essentially, following the NPS manager's 1989 objectives). This evaluation would allow NPS and Navy managers to make decisions about the ship based on sound scientific fact, not speculation and media dramatization. The discussions and the concern of Deputy Under Secretary of Defense (Installations and Environment) Raymond F. Dubois, Jr. ultimately lead to project funding from the Department of Defense Legacy Resource Management Fund, which the NPS received from 2002–2005, to plan and execute a multi-year, interdisciplinary project to assess *Arizona*'s corrosion rate and evaluation the nature of the environmental hazard posed by the oil (Russell and Murphy 2003, 2004; Russell, et al. 2004). This funding, which was about half that requested, was leveraged with funding sources from NPS-SRC, the NPS Systemwide Archeological Inventory Program, *Arizona* Memorial Museum Association, several academic institutions and corporate partners, to conduct the research presented in this report.

Although the oil issue was the major impetus for project funding, primary research focus has always been to develop an overall, long-term preservation plan for *Arizona*, which would include investigating the hull's corrosion rate to determine the possible timing of a major oil release. The first step in the research process was to determine the corrosion rate of *Arizona*'s steel hull—how quickly the ship is deteriorating—and therefore, how long before the oil's release becomes imminent. To fully understand corrosion rate, it is necessary to know the precise mechanism of corrosion and the variables involved. Understanding the corrosion mechanism and variables is necessary to extend measured corrosion rates to parts of the ship that are not directly accessible to researchers, such as the interior and areas of the hull below the harbor bottom. Predicting corrosion rate in all parts of the hull, including those where it cannot be directly measured, is necessary for designing and constructing an accurate predictive model of hull deterioration. Ultimately, this predictive model is the USS *Arizona* Preservation Project's main product and project outcome (see Chapter 6).

<u>Oil Removal versus Site Preservation</u>

Inevitably, however, we end up back at the question of oil removal: should preservation of a historically and internationally-significant war grave take precedence over a potentially invasive environmental remediation? USS *Arizona*'s significance is not merely historical, but is also symbolic. As Edward T. Linenthal notes in his book *Sacred Ground: Americans and Their Battlefields*, battlefields, including Pearl Harbor, are "prime examples of sacred patriotic space where memories of the transformative power of war and the sacrificial heroism of the warrior are preserved….The urge to preserve and restore these holy places of the nation comes from an intuitive sense that the essence of America can be found in our sacred environments…[and]…these battlefields provide a conduit through which citizens are able to participate in the power of a heroic past – a past that continues to demand allegiance to its cherished principles" (Linenthal 1991:3-4). Furthermore, Delgado (1989:169) notes, "Pearl Harbor, particularly the USS *Arizona*, has become a national shrine. Pearl Harbor and every trace of the American forces that defended it are now imbued with an almost religious significance." More than 1.5 million people each year visit the Memorial, but "perhaps more important than the modern memorial that straddles *Arizona* is the battleship itself, which is the ultimate shrine. Resting in the silt of Pearl Harbor, the USS *Arizona* is a naval memorial and a war grave. It was the scene of tragedy, triumph and heroism….The wreck now serves as a 'temporal touchstone,' drawing visitors who reflect on the tragedy of the Pearl Harbor attack…" (Delgado 1989:173). In this regard, the site is an important part of the national consciousness.

As we like to characterize the situation, if *Arizona* were any other ship in any other harbor, the oil may have already have been removed. The U.S. Navy and several commercial firms have the technical capability to empty sunken ships of environmentally harmful fluids. In 2002, the U.S. Coast Guard and Titan Maritime, Inc. removed approximately 100,000 gallons of heavy fuel oil from SS *Jacob Luckenbach*, a cargo ship sunk in a collision off San Francisco in 1953, although approximately 29,000 gallons remain (Luckenbach Trustee Council 2006). The following year, the U.S. Navy Naval Sea Systems Command (NAVSEA) removed nearly 2 million gallons of oil from USS *Mississinewa* (AO-59) a US Navy oiler, sunk on November 20, 1944 in Ulithi Lagoon, Micronesia by a *Kaiten* (an Imperial Japanese Navy manned suicide torpedo with a 3,418-lb. warhead)(US Navy 2003). These two vessels represent the range of difficulty of oil removal, with *Luckenbach* the more difficult. Both vessels are more than 100 feet deep, and both had direct access to oil containment. The *Mississinewa* removal was completely successful; the *Luckenbach* effort was not, although costing nearly $20 million. Oil removal on USS *Arizona* would set the range of difficulty beyond that of *Luckenbach*, and oil removal without sacrificing the structure may not be possible. The fact remains, however, that USS *Arizona* is not just any ship in any harbor, and other factors besides straightforward oil removal need to be considered.

Although oil removal may be potentially possible, it would be an extremely invasive procedure. *Arizona*'s fuel oil bunkers are spread across three deck levels as well as the double bottom, and arranged from bow to stern. The bunkers are highly compartmentalized and individually piped, designed that way so as to prevent catastrophic fuel loss should one part of the battleship sustain a crippling blow. There is no single fuel compartment or storage area, such as on the examples given above, so it is no simple job to "hot tap" the hull to remove the oil. Further complicating matters, all the fuel oil storage bunkers are beneath the present harbor bottom—the ship is sunk into the sediment of Pearl Harbor to its original waterline, making direct access to the bunkers impossible, and the vessel may be full of sediment in the lower areas. Given that oil removal would likely be highly damaging and destructive course of action, the question remains, is this invasive and potentially damaging procedure appropriate or acceptable on a site of USS *Arizona*'s significance? Would it be acceptable even if easier and less invasive? Most, including the NPS, think not, at least not without considerably more information about the impact to the ship as a whole and the remains of its crew specifically. Given the national importance and symbolic significance of *Arizona*'s remains, at this point the balance is decidedly tipped in favor of historic preservation over correction of a minor environmental impact and an as yet unknown environmental hazard of catastrophic oil release. Determining the true nature of the hazard based on scientific investigation provided a major impetus for the project reported here.

Besides the question of oil removal, the other looming management question will be whether intervening in *Arizona*'s natural process of deterioration is warranted, feasible, or desirable. Before weighing the benefits of a potentially very costly and unproven intervention, more information is necessary about various cathodic protection systems and their potential feasibility and effectiveness, as well as how they would affect interior spaces of the ship that cannot be directly protected. Oil remediation other than removal must be considered for the long term. The decision as to whether it is in society's interest to allow the ship to follow a natural course of deterioration, or to intervene in an attempt to prolong *Arizona*'s existence as a structure, remains to be made.

PROJECT DESIGN AND PARTNERS

The primary project focus was to acquire requisite data from the site and its environs to understand and characterize the complex corrosion and deterioration processes affecting *Arizona*'s hull, both internally and externally, and to model and predict the nature and rate of structural changes resulting from corrosion. The research program, which is outlined in more detail in the next chapter, was designed to be a cumulative progression of multi-disciplinary investigative steps orchestrated by the NPS and incorporating a long-term management perspective. Multiple lines of evidence were pursued simultaneously, some concurrently, some consecutively, each directly or indirectly linked to the others and to the overall project objectives. Operationally, we followed a two-fold strategy of research combined with long-term monitoring. Primary research was directed towards characterizing the overall corrosion processes and determining internal and external corrosion rates. These data were required to develop a predictive model of how *Arizona* is deteriorating, when corrosion will reach the point where structural changes indicate imminent collapse and how that collapse will take place to provide predictability through monitoring. Monitoring activities, which are ongoing, were initially aimed at collecting baseline data for inclusion in corrosion analysis, and are now being used to assess changing conditions over the long-term and to serve as a test for the validity of the mathematical model.

The SRC provided project principals who had been involved in *Arizona* research from the early 1980s (see Lenihan 1989b). We also partnered with other NPS programs (particularly the NPS Resources Inventory and Monitoring Division and NPS GPS Coordinator), military units (U.S. Navy, Mobile Salvage Diving Unit One, Naval Facilities Engineering Service Center, Navy Region Hawaii, Naval Station Pearl Harbor; U.S. Army, 29th Engineer Battalion Survey Platoon; and U.S. Air Force, Eglin Air Force Base), academic institutions and researchers (University of Nebraska, Lincoln; Medical University of South Carolina; Harvard University;

University of Michigan; and University of New Mexico), commercial companies (Discovery Channel; History Channel; HydroFlex; Inspection Technologies, Inc.; National Geographic Magazine and Television; Ocean Technology Systems; Titan Maritime, LLC; Trimble Navigation (+ surveying company), TruVue Imaging; USIA Drysuits, and VideoRay, Inc.), non-profit organizations (Coastal Maritime Archaeology Resources and *Arizona* Memorial Museum Association), and other federal agencies (National Institute of Standards and Technology; National Oceanic and Atmospheric Administration; U.S. Geological Survey, Marine Facility; U.S. Geological Survey, Pacific Science Center; and Naval Historical Center) in addressing the multifaceted questions confronting managers responsible for both USS *Arizona*'s preservation and associated environmental risk. This research partnership is an example of public and private institutions working together effectively for public benefit, and it serves as a model for combining resources to cost-efficiently address issues important to the American people.

ORGANIZATION OF THE VOLUME

Conceptually, this report is divided into four sections. Part I includes chapters that present background information necessary for understanding the development of the USS *Arizona* Preservation Project and for interpreting project results within their broader context. In addition to this introductory chapter, Chapter 2 outlines a detailed research design, explaining each element of the research program in detail and discussing how each element contributes to the larger project goals. This chapter is important for understanding why we chose the specific research directions that we did for the project. The final chapter of Part I is a historical background chapter highlighting cultural site formation processes, which is vital for understanding how the site came to be in the physical condition it is today. This chapter discusses battle damage, US Navy salvage from 1941 to 1943, early memorials and other structures erected on the hull, superstructure removal during the early 1960s in preparation for building the current memorial, and detailed analysis of final vessel configuration and post-depositional salvage and how that has affected its present site condition and state.

The second part of the report consists of individual chapters focused on each of the primary research components. Each chapter is authored by investigators from respective agencies and institutions who had primary research responsibility for each particular segment of research. The first chapter in Part II (Chapter 4), by researchers from the U.S. Geological Survey, outlines the environmental baseline for the site based on long-term deployment of oceanographic and environmental instruments that collected various parameters for more than a year. Long-term data collected from outside the hull is combined with internal data collected with instruments mounted on a small, remotely operated vehicle (ROV) to give an overall environmental characterization of the site. These data are critical for assessing the corrosion rate of the steel hull.

The next chapter (Chapter 5), authored by researchers from the University of Nebraska, Lincoln, outlines the results of nearly a decade of corrosion research on *Arizona*'s hull. It discusses the full array of theoretical, experimental, and practical applications of corrosion science deployed to understand the specific corrosion processes affecting the battleship, as well as our best determination of corrosion rate for different parts of the hull.

Chapter 6 focuses on the Finite Element Analysis of *Arizona*'s hull conducted by scientists from the National Institute of Standards and Technology (NIST). This analysis is the primary product of the USS *Arizona* Preservation Project, and represents the first time that such a detailed, computer-based finite element model (FEM) has been used in maritime archaeological research. The chapter discusses the creation of the *Arizona* FEM by NIST, including assumptions and model parameters incorporated within the model, scenarios that were run, and implications for projections of long-range deterioration of the vessel.

Chapter 7, contributed by Harvard University microbiologists, outlines the results of preliminary experimental research (not completed as yet because of partial funding) identifying the role of microbial induced corrosion in *Arizona*'s deterioration, particularly in oil-containing spaces deep inside the lower spaces of the ship. This research offers a critical glimpse of the ship's interior spaces that are completely inaccessible to researchers, and that were instead recreated in the laboratory to predict current conditions.

The final chapter of Part II (Chapter 8) outlines a research program directed at characterizing *Arizona*'s oil, including identifying specific biomarker fingerprints to identify oil from *Arizona*, as well as an evaluation of oil leaking for various locations around the ship. This chapter also examines and identifies a microbial film that covers oil trapped in compartment overheads, as well as stepping back to characterize the broader distribution of oil from *Arizona* around Pearl Harbor.

The report's third section (Part III) describes aspects of the on-going monitoring program on USS *Arizona*, primarily structural monitoring using high-resolution Global Positioning System (GPS) receivers capable of sub-centimeter accuracy, oil release measurements and artifact tracking. This monitoring program, initiated in 2001 by SRC, will determine if *Arizona*'s remains are stable or if there is active movement, settling or shifting of the hull. Subsequent occupations of our GPS monitoring network in 2003 and 2006 revealed no discernible movement. The monitoring program is described in detail in Chapter 9. In addition, as a control for geological factors that might be the cause of any future observed movement, Chapter 10 discusses the research to establish a geological baseline through subsurface geophysical survey and through geotechnical analysis of both physical cores from around the battleship, and using advanced geophysical techniques to determine whether *Arizona* is supported by stable sediments. Full characterization of sediments immediately around and beneath *Arizona* serves as a critical control for evaluating any future structural movements that may be observed.

Finally, Part IV consists of summary, conclusions, and recommendations that have resulted from the overall research program to date. Chapter 11 summarizes and evaluates the data within a site preservation framework, brings our multiple lines of evidence together in a comprehensive way to address our simple question, "what's happening to what's there?" and outlines a series of site preservation recommendations based on cumulative research results.

REFERENCES

Cummins, G. and B. Dickinson

1989 The Management Experience. In *Submerged Cultural Resources Study: USS Arizona Memorial and Pearl Harbor National Historic Landmark*, edited by D. J. Lenihan, pp. 157-168. Submerged Resources Center Professional Papers No. 9. National Park Service, Santa Fe.

Delgado, J. P.

1989 Memorials, Myths and Symbols. In *Submerged Cultural Resources Study: USS Arizona Memorial and Pearl Harbor National Historic Landmark*, edited by D. J. Lenihan, pp. 169-183. Submerged Resources Center Professional Papers No. 9. National Park Service, Santa Fe.

1992 Recovering the Past of USS Arizona: Symbolism, Myth, and Reality. *Historical Archaeology* 26(4):69-80.

Gould, R. A.

2000 *Archaeology and the Social History of Ships*. Cambridge University Press, Cambridge.

Henderson, S.

1989 Biofouling and Corrosion Study. In *Submerged Cultural Resources Study: USS Arizona Memorial and Pearl Harbor National Historic Landmark*, edited by D. J. Lenihan, pp. 117-156. Submerged Resources Center Professional Papers No. 9. National Park Service, Santa Fe.

Jeffery, B.

2004 World War II Underwater Cultural Heritage Sites in Truk Lagoon: Considering a Case for World Heritage Listing. *International Journal of Nautical Archaeology* 33(1):106-121.

Kelly, M.

1996 Enshrining History: The Visitor Experience at Pearl Harbor's USS Arizona Memorial. *Museum Anthropology* 20(3):45-57.

Lenihan, D. J.

1989a Introduction. In *Submerged Cultural Resources Study: USS Arizona Memorial and Pearl Harbor National Historic Landmark*, edited by D. J. Lenihan, pp. 1-12. Submerged Resources Center Professional Papers No. 9. National Park Service, Santa Fe.

1989b *Submerged Cultural Resources Study: USS Arizona Memorial and Pearl Harbor National Historic Landmark*. Submerged Resources Center Professional Papers No. 9. National Park Service, Santa Fe.

Lenihan, D. J. and L. E. Murphy
1989 Archeological Record. In *Submerged Cultural Resources Study: USS Arizona Memorial and Pearl Harbor National Historic Landmark*, edited by D. J. Lenihan. Submerged Resources Center Professional Reports No. 9. National Park Service, Santa Fe.

Linenthal, E. T.
1991 *Sacred Ground: Americans and Their Battlefields*. University of Illinois Press, Chicago.

Luckenbach Trustee Council
2006 *S.S. Jacob Luckenbach and Associated Mystery Oil Spills Final Damage Assessment and Restoration Plan/Environmental Assessment.* Prepared by California Department of Fish and Game, National Oceanic and Atmospheric Administration, United States Fish and Wildlife Service, National Park Service.

Rodgers, B. A., W. M. Coble and H. K. Van Tilburg
1998 The Lost Flying Boat of Kaneohe Bay: Archaeology of the First US Casualties of Pearl Harbor. *Historical Archaeology* 32(4):8-18.

Russell, M. A. and L. E. Murphy
1997 Minimum Impact Archaeology. In *Encyclopaedia of Underwater and Maritime Archaeology*, edited by J. P. Delgado, pp. 278-279. British Museum Press, London.

2003 *"Long-Term Management Strategies for the USS Arizona: A Submerged Cultural Resource in Pearl Harbor, Hawaii." Legacy Resources Management Fund Project No. 02-170: 2002 Annual Report*. Submerged Resources Center Technical Report No. 14. National Park Service, Santa Fe.

2004 *"Long-Term Management Strategies for the 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. National Park Service, Santa Fe.

Russell, M. A., L. E. Murphy, D. L. Johnson, T. J. Foecke, P. J. Morris and R. Mitchell
2004 Science for Stewardship: Multidisciplinary Research on USS Arizona. *Marine Technology Society Journal* 38(3):54-63.

U.S. Navy
2003 Overview of Survey/Salvage Operation: USS Mississnewa, www.supsalv.org/00c2_posseA0_59.asp?destPage=00c2.

Vesilind, P. J.
2001 Oil and Honor at Pearl Harbor. *National Geographic Magazine* 199(6):84-99.

CHAPTER 2

Research Design

Matthew A. Russell and Larry E. Murphy

INTRODUCTION

Researchers from the National Park Service's (NPS) Submerged Resources Center (SRC) designed the USS *Arizona* Preservation Project from the outset to be multi-year, interdisciplinary and cumulative, with each element contributing to provide the basic research required to make informed management decisions for long-term preservation and to minimize environmental hazard from fuel oil release. In addition, we designed the project to serve as a model for interdisciplinary, management-based science that has direct application to preservation and management of historical iron and steel vessels worldwide, particularly serving as a guide for intervention actions directed at other historic vessels leaking contaminants into the environment.

We viewed this research design not only as an overall guide for fieldwork and analyses, but also as a "living document" that continued to change and evolve as the research progressed, as analyses resolved some issues and as questions became more focused. Even beyond this project, the NPS will continue to revise the research and monitoring on USS *Arizona* to incorporate evolving research approaches, results and questions. This research design has had significant peer review in both academic publications and professional meetings: portions of this research design have been previously published in Russell and Murphy (2003; 2004) and Russell et al. (2004); it has been presented and discussed twice at the National Academy of Science, Ocean Studies Board subcommittee (Murphy 2002 and 2003); presented to the Society for Historical Archaeology (Murphy and Russell 2006); the George Wright Society (Murphy 2003); and it has been presented to many public and interested veteran groups, for example, the 60th Commemoration of the Pearl Harbor Conference in 2001 (Murphy 2001). In addition, individual scientists involved in the USS *Arizona* Preservation Project developed research approaches and have presented findings and results to peer organizations and published in academic journals. These are discussed in appropriate chapters and a compilation of research results, presentations and publications is presented in the final chapter of the report.

GOALS AND OBJECTIVES

The USS *Arizona* Preservation Project builds upon pioneering site documentation and research led by the National Park Service's Submerged Cultural Resources Unit (later renamed SRC) in the 1980s. The early SRC investigations initiated *in situ* documentation and study of large, submerged steel warships both in the U.S. and internationally (Lenihan 1989). The current project, building upon work done in the 1980's, was designed to provide a broad-based foundation for long-term preservation, management and monitoring of USS *Arizona*.

The primary project focus was to acquire requisite data for understanding and characterizing the complex corrosion and deterioration processes affecting *Arizona*'s hull, both internally and externally, and to model and predict the nature and rate of structural changes resulting from corrosion. Developing reasonable and effective management alternatives and deciding the most desirable actions, particularly those regarding intervention or rehabilitation, could not be effectively done without this information. The current research program was viewed as a critical step in obtaining necessary scientific information upon which to make sound management decisions. A central goal of this research was to develop and recommend short-term and long-term management plans for site preservation based on the results of the research program.

The USS *Arizona* Preservation Project addresses another important issue besides preservation of an internationally important site. USS *Arizona* contains several hundred thousand gallons of fuel oil that has been slowly escaping since its loss in 1941. This oil, a potentially serious environmental hazard, is contained within the corroding hull. *Catastrophic oil release, although by all indications not imminent, is ultimately inevitable.* Understanding the complex hull corrosion processes, structural changes and oil release patterns offers the most effective and efficient method of mitigating this potential hazard. One of the goals of this project, therefore, was to develop a research strategy for environmental impact risk assessment and abatement to address the oil issue.

Because of the particular national importance of *Arizona*, any solution to the oil issue must incorporate a minimum-impact approach so that long-term site preservation will not be compromised. We conducted all research and monitoring operations with the respect due an American war grave and with minimum impact to the site consistent with NPS principles of stewardship and preservation; no diver entered the vessel. Addressing the oil release problem within a site-preservation framework provides the best balance between the competing social values of preservation and ecology, and it has the highest probability of arriving at the optimal solution for both issues.

Unnecessary disturbance to *Arizona*'s hull is likely to be seen by many as more problematic than the limited oil release now occurring, although managers will ultimately have to face the possibility of a larger release. This has in effect already been done. Because of the nature of Pearl Harbor, there is extensive oil recovery capability staged at Pearl Harbor, and a contingent of practiced professionals stand ready as a response team for oil spills.

PRINCIPAL RESEARCH DOMAINS AND METHODOLOGY

The SRC provided project principals who have been involved in *Arizona* research from the early 1980s (see Lenihan 1989). We also partnered with military units, researchers, academic institutions, commercial companies, research laboratories, professional societies and other federal agencies to address the multifaceted questions confronting managers responsible for both USS *Arizona*'s preservation and any associated environmental risk. This research program was designed to be a cumulative progression of multi-disciplinary investigative steps. Multiple lines of evidence were pursued simultaneously, each directly or indirectly linked to the others and to the overall project objectives. Operationally, the NPS followed a general strategy of intensive research to develop a predictive model of hull deterioration that could be tested and revised and through long-term monitoring of critical variables.

Primary research was directed towards characterizing overall corrosion processes and determining internal and external corrosion rates. These data were required to develop the predictive model of how *Arizona* is deteriorating and when corrosion will reach the point where structural changes indicate imminent collapse and potential release of oil. The study of iron and steel corrosion of historic material in marine environments began in the mid-1970s. Archeologists and conservation specialists in Australia conducted pioneering research on iron artifacts and later on iron and steel shipwreck deterioration and determined that the major factors affecting shipwreck corrosion are metal composition and metallurgical structure, marine growth, water composition, temperature, extent of water movement, seabed composition and depth of burial beneath the seabed (North and MacLeod 1987:68). Collecting data necessary to characterize critical corrosion processes, building on our prior work on USS *Arizona* (Lenihan 1989) and on the Australian experience, involved evaluating each of these factors, as well as identifying additional unrecognized complex and interrelated processes that affect corrosion in many different ways. When attempting to determine the corrosion history of an object, it must be considered individually—there are very few oceanographic and environmental parameters that are uniform between sites. However, during the course of this research we sought general principles and methods that could be applied from what was learned on *Arizona* to other legacy vessels containing contaminants, which is a global problem. In addition to corrosion research, related research focused on the oil that remains trapped within *Arizona*'s hull and on the geological substrate supporting the ship.

Data collection activities were aimed at not only characterizing the active processes, but also collecting baseline data for inclusion in corrosion analysis that could be used to assess changing conditions and rates over time. These data were used to quantify various on-site conditions such as physical movement of the ship and oil release amounts. Research and monitoring activities are broken down into individual research domains discussed below. Each research domain either directly contributes to primary research goals or plays a key supporting role in project objectives. All are interconnected on some level.

FINITE ELEMENT ANALYSIS

Principal Questions: How can the cumulative results of *Arizona* research be used for modeling and predicting long-term changes in the hull, and how and when will those changes occur? Can a predictive model be developed that will allow incorporation of new data and information? How do we validate such a model?

Finite Element Analysis (FEA) was the principal research method used to produce the primary predictive tool that forms the centerpiece of USS *Arizona* research. A Finite Element Model (FEM) is a computer-manipulated mathematical model that calculates theoretical stresses and shape changes in a structure under load using experimental variables based on observationally-derived data. The FEM divides a complex solid into many small components called *elements*, each of which can be one of numerous simple shapes. Properties for the material of each element are input into the software to describe the element's behavior between its end (or finite) points (for example, mechanical properties, heat flow, density, etc.). The end points of each "finite" element are called *nodes*. Conditions are set regarding how nodes connect to one another and loads (known as boundary conditions) are added to the model. As each individual element changes under different boundary conditions, it transmits a slightly changed boundary condition to neighboring elements, which then repeat the process. The result are plots of displacements of nodes and calculated stresses in the structure at all points—taken in the aggregate, the displaced nodes and stresses of all the elements in the FEM offers a predictive model of stress and change under different conditions for an entire structure.

For historical shipwrecks such as USS *Arizona*, an FEM allows manipulation of multiple variables, such as corrosion rate and hull thickness, to analyze loads and stresses on hull structure for predicting structural change, probable collapse rate, its nature, sequence and consequent impact on structures containing fuel oil. In addition, the FEM provides a fundamental tool to evaluate consequences of proposed management alternatives involving structural intervention or preservation strategies. There are particular difficulties in applying FEMs to shipwrecks, however. Geometry is constantly changing due to ongoing corrosion, loads can be very complex, and load and corrosion interact in such a way as to increase the complexity of the model (for example, stress corrosion cracking). There are ways to overcome these difficulties, but accurate data based on direct measurements and observations are of primary importance. For the model to be representative of actual conditions, input data such as structural dimensions and connections, corrosion rates and loads must be as precise as possible.

Baseline FEM development was conducted by the National Institute of Standards and Technology (NIST) and focused on modeling the *Arizona* hull structure in its as-built original state for an 80-ft. cross-section, amidships from frame 70 to 90. The 80-ft hull length selected for initial modeling represents the sternmost area affected by the blast that sank the vessel and the ensuing fire. The reason for this selection is that it was believed to be conservative; that is, corrosion in this area would likely be highest, which would incorporate a conservative element into the model when applied to the remainder of the stern, which is in better shape. For maximum precision, the entirety of the stern must be subjected to FEA based on direct corrosion rates. Because this was pioneering research in the sense that FEA has not been applied to corrosion and deterioration of a historical shipwreck before, this preliminary model was a necessary step to refine and test methodologies for developing the overall model required for predicting present and projected future structural strength. It is important to note that the great majority of the work in creating a FEM of a structure is in the generation of the model and mesh in the computer. Remediation scenarios can then be tested and further stability studies can be made by simply changing the inputs and accounting for new measurements, ideas or to test other scenarios.

The next development stage of the FEM was to incorporate structural effects of the blast and fire that sank the vessel. Modeling the structural changes to *Arizona* resulting from the explosion and subsequent fire that sank the ship was the logical starting point for understanding the vessel's present condition and projecting its future condition and rate of deterioration. (Unfortunately, this portion of the research remains unfunded.)

The final stage of FEM development incorporated external and internal corrosion and thickness measurements to complete the model of *Arizona*'s present condition and to allow researchers to extend the model into the future. Predictions about current status and future collapse vary in accuracy depending on the detail of the input data, crafting the correct boundary conditions, and by minimizing simplifying assumptions. For the first issue, the greatest deficiency in data in this case was knowledge of the actual thickness and conditions of hull features both internally and below the present harbor bottom. All other assumptions and simplifications have a much smaller effect on the results than these data. The boundary conditions were similarly difficult, as the hull is being supported by a water saturated semi-solid that moves relative to the hull.

As the primary "product" of the current research program, much of the data collected during field work and as a result of the ongoing monitoring was designed to be fed directly into revising and refining the FEM to make it as accurate as possible. When combined with corrosion rates and other variables, the model provides predictability required for evaluating timing, necessity and long-range consequences of management actions.

If monitoring change in *Arizona*'s structure over time conforms well with changes predicted by the FEM, researchers will have confidence in extending the model's predictions to areas of the ship (such as the lower decks) that are difficult to access directly for monitoring purposes. If monitoring changes does not accord well with the predictions of the FEM, the disjunction between real and predicted behavior will alert researchers to modify the FEM, gather new data that may have been overlooked in the initial model, or both. Beyond the course of this investigation, we anticipate a dynamic give and take between the FEM and ongoing research.

CORROSION ANALYSIS

Principal Questions: What is the nature and rate of corrosion taking place on *Arizona*? How does concretion formation affect corrosion rate? Is there a difference in corrosion rate among the 1916 steel, the 1930 refit materials, and structure affected by the blast and fires?

Corrosion research on USS *Arizona* focused on understanding and characterizing the specific nature of corrosion occurring on the vessel and determining the corrosion rate for different structural elements of the ship. The goal was to establish a curve of deterioration and "plot" where *Arizona* currently falls on that curve. The rate of corrosion is a crucial parameter necessary for making long-term predictions about *Arizona*'s structural integrity using the FEM. Because the battleship is a large, complex three-dimensional structure, and it is impossible to directly measure corrosion rates for all critical elements, (currently, there are more than 52,000 elements in the FEM) there was necessarily some generalizing and use of inferential data to derive deterioration rates, particularly for inaccessible internal structures. In addition, a comprehensive understanding of all relevant parameters, such as hull steel chemistry and microstructure, constituent analysis of concretion covering the ship and seawater chemistry, was necessary for making indirect estimates of overall corrosion rates.

The most accurate measure of corrosion rate at our disposal was to compare current structural steel thickness with original thickness found on ship's plans, determine how much metal has been lost over a specific period of time and use the calculated corrosion rate in a linear extrapolation to determine overall corrosion rate for that particular location. Cumulative corrosion analyses ultimately may provide a more accurate variable rate. Present indications are that corrosion rates are initially high soon after submergence, and then they decrease significantly.

Although it was possible to remove some small (10 cm, 4-in. diameter) hull samples (coupons) for direct comparison, in most cases it was not feasible to take direct measurements of steel hull thickness because of the destructive nature of the process and inaccessibility of interior features. Because research on *Arizona* must be carried out in the most non-invasive manner possible, other less-destructive methods for calculating corrosion rate, including ultrasonic thickness measurements, had to be devised, some of which will rely on inferences made from the few direct measurements we had and by comparing other variables critical to the corrosion process. Because the physical environment plays such a large role in how corrosion takes place, baseline environmental data are important in general (see below), but specifically the environment at the hull/concretion interface had to be characterized since that is where corrosion occurs (Johnson et al., this volume).

Exterior Corrosion Analysis

Metallurgical and Metallographic Analysis

Metallurgical and metallographic analyses were designed to establish basic chemical, structural and strength characteristics of steel used in *Arizona*'s original 1914–1915 construction and later 1929–1931 reconstruction. Investigation of steel hull samples was a necessary step towards determining corrosion nature and rate. Analysis originally focused on steel collected from superstructure elements stored on land at Waipio Point, Hawaii that were removed from *Arizona* before construction of the Memorial began in 1960. Samples from both the 1914–1915 and 1929–1931 construction periods were analyzed by scientists from University of Nebraska, Lincoln (UNL). Tests performed include chemical constituent analysis, microstructural examination and Charpy impact testing to determine basic strength characteristics (Johnson, et al. 2000).

Additional metallurgical and metallographic analyses were performed on hull coupons collected *in situ* from *Arizona*'s hull. Four-inch (10 cm) diameter hull samples, including intact exterior and interior concretion, were removed using a purpose-built hydraulic-powered hole saw. A total of eight coupons were removed from external, vertical hull locations on both port and starboard sides. On each side, one sample was taken at the Upper Deck level, near the water line; from the Second Deck level, above the torpedo blister; from the Third Deck level, in the torpedo blister; and from the First Platform level, in the torpedo blister and below the mud line. After removal, each location was plugged using a standard plumber's plastic pipe plug and sealed with marine epoxy to prevent formation of a localized corrosion cell. UNL researchers used standard metallographic methods to examine the hull coupons to measure metal thickness at Rail Sciences Laboratories in Omaha, Nebraska (Johnson et al., this volume). Additional metallurgical and metallographic analyses on the same samples were performed by researchers from NIST.

Concretion Analysis

Fundamental research into the composition and characteristics of the concretion covering *Arizona*'s outer hull was conducted to aid in understanding the kinetics of the corrosion process on the ship and to determine how concretion chemistry correlates with hull metal loss. The hard layer of concretion that forms on iron and steel objects in seawater is a combination of iron corrosion products and marine organisms. Initial organisms are pioneering coralline algae that leave layers of calcium carbonate when they die. The calcium carbonate residue is overlaid by subsequent layers of coralline algae, and the increasing calcium carbonate layers forms a suitable substrate for secondary growth, such as soft corals and mollusks (Henderson 1989; North 1976:254). Outwardly diffusing iron ions replace some of the calcium resulting in a mix of iron corrosion products, calcium carbonate and living marine organisms covering the iron or steel object. The concretion forms a semi-permeable barrier between the bare metal and seawater and has a significant influence on corrosion by reducing the amount of dissolved oxygen available for the corrosion reaction, increasing acidity at the metal-concretion interface and increasing the chloride ion concentration (North 1976:253).

Concretion investigation on USS *Arizona* focused on x-ray diffraction to isolate compounds that make up the concretion and environmental scanning electron microscopy (ESEM) to determine relative percentages of each element. X-ray diffraction was conducted by the Air Force Research Laboratory, Eglin Air Force Base, while ESEM analysis was completed by the Composite Materials and Structures Center at Michigan State University. Preliminary results of *Arizona*'s concretion analysis are consistent with North's (1976) findings that concretion formed on wrought and cast iron structures contains the mineral siderite, which is formed by the exchange of iron ions for calcium ions. UNL scientists researched how density and electrical resistivity of *Arizona*'s outer hull concretion could be used to characterize the corrosion process and how concretion analysis could be used to indirectly infer corrosion rates, a technique applicable to other sites.

In Situ Hull Corrosion Measurements

When iron or steel is placed in seawater, corrosion begins as a reaction in which the oxidation of metal forms the anodic portion of a corrosion cell, and the consumption of oxygen forms the reduction, or cathodic, part of the reaction. When oxidation and reduction rates are equal, there will be a voltage that characterizes the specific reaction rate (or corrosion rate)—that characteristic voltage is known as the corrosion potential (E_{corr}). In general, a more negative E_{corr} value indicates a lower corrosion rate while a more positive E_{corr} indicates a higher corrosion rate (MacLeod 1987:49-50).

In situ E_{corr} was measured on *Arizona*'s hull using a silver-silver chloride (Ag/AgCl) reference electrode giving a voltage measurement in millvolts (mV). In addition to E_{corr}, pH is another critical parameter giving an indication of corrosion, and the combined data can be directly related to appropriate Pourbaix Diagrams. The Pourbaix Diagram, a two dimensional map of E_{corr} vs. pH, shows regions of stability for corrosion products as a function of E_{corr} and pH and identifies limits for corrosion, immunity from corrosion or limits for formation of protective layers on the metal surface. Diagrams for iron/water and iron/water/CO_2 are especially useful in characterizing corrosion processes at the steel/concretion interface and into the concretion itself (Johnson et al., this volume). In normal seawater, pH ranges from 7.5 to 8.2, but levels below 6.5 and as low as 4.8 are found under concretion covering actively corroding metal. Lower pH levels (more acidic) typically characterize increased corrosion levels (North and MacLeod 1987:74).

In situ corrosion measurements taken systematically along *Arizona*'s hull included pH and E_{corr}. At selected stations on the vessel, pH and E_{corr} was measured at various concretion-depths using pH and Ag/AgCl reference electrodes inserted into holes drilled into the concretion. Hole depths were controlled by several depth jigs to provide uniform data through levels of concretion to the metal surface. Multiple samples were drilled in a vertical transect at each station at varying water depths to characterize how the corrosion process changes with water depth and concretion thickness. In addition, these data were compared over multiple field seasons. Correlation of E_{corr} with corrosion rate was also examined (Johnson et al., this volume).

Another critical *in situ* measurement of USS *Arizona*'s hull included ultrasonic thickness measurements. The eight hull coupons collected in two vertical transects on *Arizona*'s hull provided an empirical measure of corrosion rate at each of these locations when compared to as-built hull thicknesses. Because of the invasive nature of collecting hull coupons, however, it was necessary to develop a more non-invasive technique to expand hull thickness data. Because the specific metal thickness was precisely measured at the eight coupons locations, they provided an excellent control for testing ultrasonic thickness techniques and instruments. Corrosion pits on the interior and exterior of *Arizona*'s steel plates made ultrasonic measurements of plate thickness impractical with current technology, and ultimately, other methods, including corrosion rate based on concretion parameters, proved more reliable.

Interior Corrosion Analysis

Analysis of the nature and rate of interior corrosion on USS *Arizona* was limited to indirect measurements of environmental parameters and E_{corr}, subjective observation of interior conditions based on images taken by a VideoRay remote operated vehicle (ROV), and experimental evaluation of ultrasonic thickness techniques using the ROV as an instrument platform. With no diver access to the inside of *Arizona*'s hull, interior data could only be collected remotely. The VideoRay ROV was the primary tool used for collecting internal data. It was used as an instrument platform to carry a YSI 600XLM Multiparameter Sonde to measure pH, temperature, salinity, dissolved oxygen, oxygen reduction potential and conductivity—the same parameters being recorded externally (see below). The ROV also carried a GMC STAPERM silver-silver chloride reference electrode to measure interior E_{corr}. An evaluation was made for use of an ROV-mounted Cygnus Ultrasonic Thickness Gauge to measure interior bulkhead thicknesses, but this technology did not prove suitable for this application.

OIL ANALYSES

Principal Questions: What is the nature of *Arizona*'s oil? How and at what rate does it degrade? What is its impact on the immediate environment of the ship? Is there a "fingerprint" that distinguishes *Arizona* oil from others? How do we measure oil leak volume?

Analysis of oil leaking from *Arizona*'s hull and trapped in accessible overhead spaces was designed to collect baseline data about the approximately 500,000 gallons of Bunker C fuel oil still remaining within the battleship. It was also used indirectly to investigate the condition of interior oil bunkers. Collaborative research focused on using oil characterization to measure environmental degradation of oil trapped within different areas of *Arizona*'s hull. Oil constituent degradation, laboratory determined, proved a useful chronometric tool. The degradation of oil was used to determine residence time of each oil cache by determining the length of time each oil release has been in contact with seawater. Medical University of South Carolina (MUSC) researchers analyzed oil samples using gas chromatography coupled to mass spectrometry in order to assess the environmental weathering of the oil and to obtain a "fingerprint" of the oil leaking from the ship by examining the biomarker profile. While Bunker C is susceptible to biotic and abiotic weathering processes in the environment, it tends to be persistent due to the increased concentration of high molecular weight hydrocarbons. Using gas chromatography-flame ionization detection (GC-FID) and gas chromatography-mass spectrometry (GC-MS) to chemically characterize oil leaking from different regions of the ship, researchers determined that oil leaking near Barbette No. 4 showed almost no detectable signs of weathering, while oil trapped in Second Deck overheads and leaking from other locations were depleted of *n*-alkanes and low molecular weight polycyclic aromatic hydrocarbons. Results of analyses could differentiate individual oil bunkers, as well as differentiate age of oil (relative to sea water exposure) in cabin overheads and being released from various locations around the battleship. These data have important implications for structural analysis and inferring structural change in the inaccessible interior. This approach provided indicators about the state of deterioration and structural changes of oil bunkers that are inaccessible in the battleship's lower deck areas.

In addition to baseline oil analysis, on-going monitoring is being conducted to measure the amount of oil escaping from the ship at several locations. Using a custom-built oil collection device, researchers periodically capture all oil escaping from each location around *Arizona*'s hull during a 24-hour collection period. This quantifies the leakage rate for long-term monitoring to see whether oil leakage from specific locations is stable or increasing. Currently, we are collaborating on development of a remote oil monitoring system that can quantify the total amount of oil being released in real-time, as well as variations in oil release rates that may correlate with changing environmental conditions, changing hull structure or both.

MICROBIOLOGY

Principal Questions: What microbially induced corrosion is taking place in *Arizona*'s interior and exterior areas, and what is the impact on structural deterioration? Can laboratory experimentation model microbially induced corrosion on the oil/bunker interface?

Microbiological analyses were pursued for several purposes. One of the main applications was to examine the role of microbially induced corrosion (MIC) in the degradation of *Arizona*'s oil bunkers. Biofilms are communities of microorganisms attached to an interface and embedded in a polysaccharide matrix produced by the microorganisms. They are ubiquitous in nature and are a common cause of corrosion. The depletion of oxygen from microhabitats within biofilms has important consequences for the corrosion of metals. Anaerobic conditions can result in the growth of sulfate-reducing bacteria (SRB), a frequent cause of MIC. Metal corrosion is driven by the hydrogenase activity of the SRB. Harvard University researchers experimentally determined the ability of hydrocarbon degrading microorganisms isolated from USS *Arizona* to degrade steel. The objective was to determine the rate of corrosion in the oil-containing bunkers in USS *Arizona*.

In addition to research into MIC, other microbiological investigations were carried out on USS *Arizona*. MUSC scientists developed innovative research to examine the role of microorganisms in fuel oil degradation and the aerobic biodegradation potential of microorganisms associated with the battleship's hull (Figure 2.5). They used denaturing gradient gel electrophoresis (DGGE) analysis to examine the microbial community structure of oil-degrading microorganisms from sediments adjacent to the USS *Arizona* that use oil leaking from the ship as their sole source of carbon. The biodegradation potential of these microbial communities was demonstrated by the extensive degradation of polycyclic aromatic hydrocarbons from Bunker C crude and produced a novel pattern of biomarker degradation.

GEOLOGICAL ANALYSES

Principal Question: How stable are the sediments upon which *Arizona* rests?

The U.S. Geological Survey (USGS) conducted an analysis of the geological substrate surrounding and beneath USS *Arizona* to determine its nature and characteristics. The basic question investigated was how stable are supporting sediments beneath the battleship, and is it possible *Arizona* is experiencing movement due to shifting or compressing sediments? *Arizona*'s overall stability within its supporting matrix is important because it can potentially affect GPS structural monitoring and the FEM. To be accurate, interpretation of GPS monitoring-point movement and predictions regarding structural stability, such as those produced from an FEM, must control for geological support variables. If movement is observed in GPS monitoring, it would be necessary to isolate potential internal changes (shifting, settling and collapsing decks and internal bulkheads) from external movement (the entire ship settling into surrounding sediments). In addition, the FEM had to take into account sediment characteristics surrounding and supporting *Arizona*'s hull, including potential differential support, to give an accurate indication of the vessel's overall structural integrity.

To conduct a comprehensive analysis of the geological substrate around USS *Arizona*, researchers used a combination of geophysical remote sensing and geotechnical analysis of recovered 15-m (50-ft) cores. Stratigraphic description and geotechnical analysis of cores recovered from around *Arizona* provided data about sediment consolidation, compression properties and triaxial shear strength of distinct strata beneath the seabed. Chirp seismic reflection data collected in a wide area surrounding *Arizona*, combined with precise correlation of sub-bottom records to geological core analysis, extend these geotechnical properties to the subsurface geological strata of Pearl Harbor surrounding the battleship. The combination of these data gave an overall indication of how stable *Arizona* is within its supporting geological matrix.

ENVIRONMENTAL PARAMETERS

Principal Questions: What is the nature of the interior and exterior environment of *Arizona*? How is *Arizona*'s environment changing? How does it affect *Arizona*'s deterioration?

A variety of factors have been identified that directly influence metal corrosion on shipwrecks, including water composition (dissolved oxygen, pH, salinity and conductivity), temperature and extent of water movement (North and MacLeod 1987:68).

Oxygen reduction is typically the main cathodic reaction occurring in steel exposed to seawater, so dissolved oxygen availability at the cathodic site controls the corrosion rate, with higher dissolved oxygen content resulting in higher corrosion. Water at the ocean's surface is generally oxygen-saturated, so overall dissolved oxygen content depends on the amount of mixing that occurs with surface water—increased water movement and mixing results in elevated dissolved oxygen levels. In addition, temperature and dissolved oxygen are inversely proportional, so lower temperature results in increased dissolved oxygen. The pH level is indicative of overall corrosion activity. In normal seawater, pH ranges from 7.5 to 8.2, but levels below 6.5 are found under concretion covering actively corroding metal. Lower pH levels (more acidic) typically characterize active or increased corrosion levels. Salinity is closely related to the corrosion rate of steel in water, so increased salinity usually results in higher corrosion rates. This is evident when comparing metal preservation in freshwater compared to seawater environments—freshwater lakes invariably lead to better preservation of iron and steel. There are several ways that higher salinity affects corrosion, including dramatically increasing conductivity (which facilitates movement of ion between anodic and cathodic areas), increasing dissolved oxygen and supplying ions that can catalyze corrosion reactions, among others (North and MacLeod 1987:74). Higher conductivity can increase corrosion by increasing the movement of ions during the corrosion process.

In general, corrosion increases as temperature increases. Under controlled laboratory conditions, corrosion rate doubles for every 10°C rise in temperature. This relationship is complicated, however, by the effect of temperature on both dissolved oxygen and biological growth. Warmer water supports increased marine growth, which contributes to concretion formation on steel in seawater and that, in turn, generally reduces corrosion rates. In addition, as discussed above, lower temperature results in higher dissolved oxygen content, which consequently means increased corrosion (North and MacLeod 1987:74).

Water movement from waves and currents on a site affects corrosion in several ways, but generally high-energy environmental conditions results in higher corrosion rates. Active water movement can contribute to mechanical erosion of metal surfaces and can also impede development of protective concretion layers by removing accumulating ions before they can precipitate and begin the concretion formation process. Waves and currents also contribute to water mixing and aeration that result in increased dissolved oxygen levels (North and MacLeod 1987:74).

Factors that affect corrosion on metal shipwrecks are complicated and interrelated. Reducing one key factor can increase another, and the results are often unpredictable. It is clear, however, that in order to understand the corrosion history of an object, even a complex object like a World War II battleship, and to begin to define the nature and rate of deterioration affecting the object, an understanding of the various environmental factors at play is necessary. An important aspect of the current research program was long-term monitoring of oceanographic and environmental parameters on USS *Arizona*. This was accomplished with *in situ* multiparameter instruments placed on the hull and on the seabed to the side of the vessel.

Exterior Environment

The USGS analyzed data from oceanographic and water-quality monitoring instruments placed on and near *Arizona* to determine long-term, seasonal variability in key parameters that affect corrosion. Researchers calibrated and deployed a SonTek Triton wave-height and current meter and a YSI 6600 Multiparameter Sonde on *Arizona* in November 2002. These instruments have internal memory and batteries and can be left *in situ* for up to 60 days, recording data multiple times an hour. The instruments were retrieved and downloaded, then recalibrated and deployed every 60 days by USAR staff. The data were sent to the SRC in Santa Fe, New Mexico, and the USGS in Santa Cruz, California, for compilation and analysis. The instruments collected baseline data including wave height and direction and current velocity and direction around the vessel, and basic environmental parameters including pH, temperature, salinity, dissolved oxygen, oxygen reduction potential and conductivity. The goal was to collect at least a two-year database to discern seasonal variation and patterns of environmental parameters within Pearl Harbor. In addition, USGS researchers deployed two RD instruments 600 kHz Acoustic Doppler Current profilers (ADCP), which collected three-dimensional vertical profile measurements of current speed and direction, single-point measurements of water temperature, and water level data, for a 30 day period in 2005. As discussed above, each of these parameters can affect corrosion rates on the ship.

<u>Interior Environment</u>

Environmental monitoring was also conducted within *Arizona*'s interior cabins to determine internal environmental conditions. Internal conditions were compared to external conditions in an attempt to infer interior corrosion nature and rate. These data were critical to developing a viable FEM that takes into account both interior and exterior hull corrosion. SRC used a VideoRay ROV equipped with a YSI 600XLM Multiparameter Sonde to measure pH, temperature, salinity, dissolved oxygen, oxygen reduction potential and conductivity—the same parameters recorded externally. Initial investigations focused on second deck cabins accessible via open portholes, as well as inside Barbette No. 3. Subsequent investigations recorded environmental parameters in Third Deck spaces—although very few of these areas were accessible to the ROV. Data from both external and internal environmental monitoring was assessed, and the results were factored in developing the *Arizona* FEM.

STRUCTURAL STABILITY DETERMINATION

Principal Questions: How stable is *Arizona*'s hull? How can we measure structural changes?

Monitoring observable changes to USS *Arizona*'s accessible external areas was designed to allow researchers and managers to quantify physical changes to *Arizona*'s fabric. As internal and external structures corrode and weaken, various parts of *Arizona*'s hull may experience shifting, settling or collapse. Since a regular NPS presence on *Arizona* began in 1982, a qualitative assessment by researchers indicated that Upper Deck areas in and around the ship's galley show signs of change—widening cracks and some deck collapse is occurring. At present, measurable change has only occurred to non-structural portions of the vessel—"non-structural" in the sense that Upper Deck areas do not contribute to the battleship's overall structural integrity, especially oil-containing structures. Most Upper Deck structures were removed from *Arizona* before construction of the Memorial, which spans the ship just aft of the galley area. Regardless, active monitoring of the entire ship, including these Upper Deck areas, is ongoing still to watch for evidence of significant structural changes.

External Stability

The primary method used to monitor physical changes to USS *Arizona*'s hull is a series of discrete real-world positions on the ship whose coordinates are derived using very high-resolution Global Positioning System (GPS) instruments. Using dual-frequency GPS receivers, researchers have set a series of monitoring points across *Arizona*'s exposed decks. Initially using stainless steel studs, later changed to PVC disks, in selected locations, NPS surveyors leveled a large, purpose-built underwater tripod over each point (Figure 2.6). Extension poles set on top of the tripod extending above the water's surface allowed the GPS antenna to be placed precisely over the desired point. Using advanced survey techniques, each point was collected with sub-centimeter accuracy in three dimensions. These points were, and continue to be, re-surveyed every two years to determine if, and how, the ship is moving, shifting, or settling. Although the accuracy of each point was mathematically calculated to about 0.5 cm (Circle of Error Probable), it will be necessary to apply a more conservative threshold of change to future monitoring re-occupations. Because of environmental conditions and differences in equipment and stadia variations, a more realistic threshold is 10 cm. Instrument error, set-up error, or most likely, nearly imperceptible antenna movement caused by water movement can create cumulative errors of up to 10 cm. Consequently, we cannot reliably attribute any observed change that is less than

10 cm to vessel movement; however, corroborative evidence would be sought for any level of change. Because the GPS points exist as a network of positions, aggregate changes in the positions of more than one point, even if less than 10 cm, could potentially indicate net movement of hull structure.

In addition to GPS, structural changes were also monitored using a series of crack monitors normally employed to measure how cracks are widening on historic building walls. These plastic monitors were affixed over numerous cracks in the Upper Deck galley where *Arizona*'s deck collapse was qualitatively observed. The crack monitors were checked periodically to see if the cracks were widening or shifting.

Internal Stability

Internal structural monitoring of USS *Arizona* was a qualitative process using the VideoRay ROV to visually examine interior areas and note observable changes over time. Interior investigation took place over multiple years in all accessible areas for measuring and monitoring interior environmental factors and corrosion parameters. During this process, overall internal structural condition was observed and noted.

CONCLUSION

This research approach for USS *Arizona* and USS *Utah* was designed to produce cumulative data whose synthesis will inform management actions to preserve the vessel for future generations. We believe this experimental approach has produced results that will contribute to the disciplines involved and be applicable to numerous iron and steel legacy vessels submerged worldwide. This research partnership for the Pearl Harbor vessels is an example of government agencies, academic institutions, military commands and private institutions working together effectively for public benefit. This collaboration is a model for combining public and private resources to cost-efficiently address issues important to the American people.

REFERENCES

Henderson, S.
1989 Biofouling and Corrosion Study. In *Submerged Cultural Resources Study: USS Arizona Memorial and Pearl Harbor National Historic Landmark*, edited by D. J. Lenihan, pp. 117-156. Submerged Resources Center Professional Papers No. 9. National Park Service, Santa Fe.

Johnson, D. L., W. N. Weins and J. D. Makinson
2000 Metallographic Studies of the U.S.S. Arizona. In *Microstructural Science Vol. 27: Understanding Processing, Structure, Property, and Behavior Correlations*, edited by W. N. Weins, pp. 85-91. ASM International, New York.

Lenihan, D. J. (editor)
1989 *Submerged Cultural Resources Study: USS Arizona Memorial and Pearl Harbor National Historic Landmark*. Submerged Resources Center Professional Papers No. 9. National Park Service, Santa Fe.

MacLeod, I. D.
1987 Conservation of Corroded Iron Artifacts – New Methods for On-Site Preservation and Cryogenic Deconcreting. *International Journal of Nautical Archaeology and Underwater Exploration* 16(1):49-56.

North, N. A.
1976 Formation of Coral Concretions on Marine Iron. *International Journal of Nautical Archaeology and Underwater Exploration* 5(3):253-258.

North, N. A. and I. D. MacLeod
1987 Corrosion of Metals. In *Conservation of Marine Archaeological Objects*, edited by C. Pearson, pp. 68-98. Butterworth & Co., London.

Russell, M. A. and L. E. Murphy
2003 *"Long-Term Management Strategies for the USS Arizona: A Submerged Cultural Resource in Pearl Harbor, Hawaii." Legacy Resources Management Fund Project No. 02-170: 2002 Annual Report*. Submerged Resources Center Technical Report No. 14. National Park Service, Santa Fe.

2004 *"Long-Term Management Strategies for the 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. National Park Service, Santa Fe.

Russell, M. A., L. E. Murphy, D. L. Johnson, T. J. Foecke, P. J. Morris and R. Mitchell
2004 Science for Stewardship: Multidisciplinary Research on USS Arizona. *Marine Technology Society Journal* 38(3):54-63.

CHAPTER 3

Historical Record: USS *Arizona* Battle Damage and Salvage

Larry E. Murphy and Matthew A. Russell

INTRODUCTION

Examination of primary documents about USS *Arizona*, particularly post-sinking salvage, was planned as part of the initial research design of the USS *Arizona* Preservation Project for a number of reasons. Several aspects of the ship's history have direct impact on a number of research domains, especially those regarding metallurgical analyses and corrosion characterization. The ship, launched June 19, 1915, underwent a major refit in 1929–1931 (Lott 1978:21-37) (Figure 3.1). The ship suffered high explosive blast effects on December 7, 1941, and it burned intensely for two days before oil and explosives fires could be extinguished. It is important to the research questions to distinguish locations of blast and fire impact on the physical structure. This impact must also be incorporated into the primary product of the USS *Arizona* Preservation Project, which is the Finite Element Model (FEM, see Chapter 6) being developed to provide the predictability requisite for management decisions about the ship. To develop both an accurate and conservative predictive model of *Arizona*'s deterioration, we had to be certain about which metallurgical samples to collect and analyze and where to take corrosion readings and understand their implications for inclusion in the FEM. Because it was impractical to initially model the entire remainder of the hull, a portion of the hull was selected to develop the FEM to test the process and to establish a likely curve of deterioration of the remaining intact hull. In the long-term, an FEM will be required for the entire ship that incorporates cumulative corrosion and experimental data relevant to hull deterioration. Analysis of historical documents describing *Arizona*'s hull damage soon after the attack and what salvage activities were conducted is discussed in this chapter. These historically based factors have been incorporated into both the sample design and in the FEM. They will also be important to developing the future complete-hull FEM.

ARIZONA'S CONDITION BEFORE AND DURING THE ATTACK

It is critical to know what *Arizona*'s condition was at the time of the attack on December 7, 1941. Two aspects are of primary interest: the amount of fuel aboard and the status of hatches and passageways in the hull. The former is necessary to develop an estimate as to the amount of oil that may remain on the site, and the latter addresses ease of access of interior spaces for measurement, monitoring or physical intervention within the hull. As a matter of National Park Service (NPS) policy, because of the status of *Arizona* as a war grave and National Historic Landmark, and also as a matter of safety, no divers entered the hull during this research project. All interior examination and data acquisition was by a VideoRay Remotely Operated Vehicle (ROV). The nature of the blast in the forward portion of the ship is also discussed here.

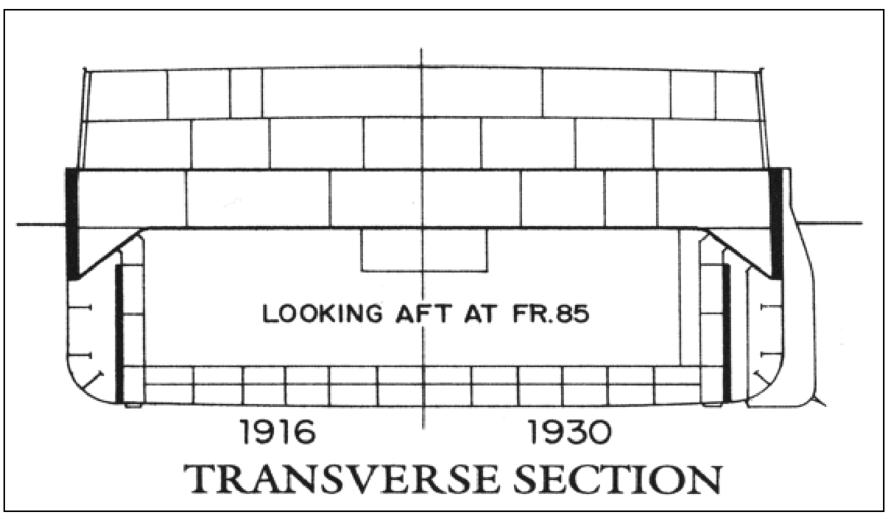

Figure 3.1. Transverse sections showing some of the structural changes to *Arizona*'s hull during 1929-1931 refit (USS *Arizona* Memorial Archives).

ESTIMATE OF OIL CONTAINED IN *ARIZONA*'S HULL

We have not located documents that indicate the amount of fuel Arizona had on board at the time of the attack. The statement by Commander Homann (1942a:2) "The outboard fuel oil tanks were filled to ninety-five percent capacity in the area of the possible torpedo hit" indicates the vessel may have been near emergency capacity.

Before the attack, *Arizona*'s draft forward was 32 ft. 6 in., while aft it was 33 ft. (Homann 1942a:1: Geiselman 1941:1). Draft measurements obtained just prior to the attack inform about the status of fuel that was aboard *Arizona* at the time of the attack.

The specific gravity of Bunker C No. 6 Fuel Oil is approximately 0.95, the higher end of the range for petroleum products. The common conversion factor for petroleum hydrocarbons of 294 gallons per ton is derived from an average specific gravity of 0.83. (National Research Council 2003:189-190). However, using the actual specific gravity for Bunker C of 0.95, Bunker C weighs about 7.6 lbs. per gal., and there would be only 263 gal. per ton. The latter figure is used here for *Arizona* oil calculations. The full load draft for the ship was 30 ft. 1¾ in. with a 4,630-ton normal load of fuel oil; emergency load draft was 33 ft. 3 in. with emergency load of fuel of 6,180 tons (Lott 1978:50). According to the battle reports, *Arizona*'s draft was about 33 ft. (Homann 1942a:1: Geiselman 1941b:1), which indicates nearly a full emergency load of fuel. An estimate of 6,000 tons of fuel aboard *Arizona* equals approximately 1,578,000 gal. An early estimate of *Arizona* hull damage after the attack indicated about 40% of the aft portion of the hull was intact (Commander Base Force to Commander in Chief, Pacific Fleet December 28 1941:6), which would extend damage aft to about frame 85 (which correlates well with other estimates, for example Geiselman 1941:1, who estimated the ship was destroyed forward of frame 88). This is somewhat less than divers' reports of the ship being intact aft of frame 70 (but that the main deck was buckled forward of frame 88). Assuming, however, the 40% estimate correct, it would be reasonable to estimate perhaps 40% of the original oil bunkers would remain undamaged to a point sufficient to contain oil. This means a reasonable estimate of the maximum oil remaining aboard *Arizona* is about 630,000 gal., or about 2,400 tons, less what has leaked since the vessel sank.

There is no direct mention of fuel oil fuel removal operations on *Arizona* in the original salvage documents reviewed so far. However, Commander Homer N. Wallin, who relieved

James M. Steele's command of the Pearl Harbor salvage operations January 9, 1942 and held that position until salvage operations were complete, reported in a summary of the salvage operations (1946:29) that "Fuel oil also was a most valuable commodity and a source scarce article in the spring of 1942. Accordingly, a large amount of oil was pumped from the intact oil tanks of these vessels [*Arizona* and *Utah*], and about a million gallons was recovered from the *Oklahoma*." Certainly, not all, if any, fuel oil was removed; both *Arizona* and *Utah* continue to leak as they have since the attack. In his later volume, Wallin (1968:268) does not mention oil removal from *Arizona*'s intact tanks, only that "the oil which fouled the harbor was gradually removed as it was released from the ship's opened tanks." Further historical research is required to verify oil removal from these vessels and the quantity recovered during salvage operations.

ARIZONA'S HULL CONDITION AT THE TIME OF ATTACK

Arizona's acting commanding officer A.J. Homann responded to queries from the Chief of Naval Operations regarding the condition on *Arizona* during and after the attack (Homann 1942b). The following discussion is from that document. Homann's response to Chief, Naval Operations was generated from interviews with survivors. At the time of his statement, January 28, 1942, divers had only investigated the main and second deck, so survivors' accounts were used to augment direct diver observations. At the time of the attack, all "X" (or "X-ray") doors and fittings were closed, due to the previous night's establishment of Material Condition X-Ray. Many of the engineering spaces, those not actually being used, were in Condition "Z" (or "Zed") and locked. This included the shaft alleys, engine rooms, firerooms, but not the dynamo, evaporators, and ice machines. The attack was so sudden, with the explosion of the forward magazine occurring so soon after the attack began, that little time was available for securing Condition Zed in those areas not already secured.

Material Condition X-Ray was the damage control condition in peacetime, when steaming in time of war when attack was improbable or unlikely, or when in port where danger from torpedoes, bombs and mines existed. Condition Zed was to be immediately deployed upon sounding of "general quarters" (Madsen 2003:69). Condition X is the minimum safety condition, while Condition Z is the battle closure condition, and Condition Y is between the two (Wallin1968:125).

In a separate correspondence to the Chief, Bureau of Ships, Homann (1942a:2) states: "The ship, at the start of the attack, was in material condition X-ray with usual water-tight doors closed below the third deck, except air ports above the water-line were open. Material Condition Zed had been partially set during the action before the ship was destroyed."

Turrets 3 and 4 were mostly secured in Condition Zed. Because there were no survivors from turrets 1 and 2, there is reason to believe they were in the same condition. Ensign Flannigan (1941:1) reported that the lower room of turret 3 was in Condition Zed. Geiselman (1941:2), *Arizona*'s first acting captain after the attack, reported that the after magazines were voluntarily flooded during the attack.

The boiler division and "B" part of the ship below the third deck was probably in Condition Zed shortly after the attack began. From survivor accounts, "it is fairly certain that Condition Zed was not completely set on the third deck and probably most of the armored hatches were still open" (Homann 1942b:1-2). Homann also states: "an early bomb hit down the stack disrupted the fire main and bilge pumps and there was no water with which to fight the fires." He also noted that survivors' statements indicated that the flooding was general after the magazine explosion, and the water filled Turret 4 at a very rapid rate, which would not occur had Condition Zed been fully secured; all watertight doors would have been sealed.

FORWARD MAGAZINE EXPLOSION

Arizona Acting Commander E.H. Geiselman reported that: "Apparently one large, possibly 2,000-lb, armor-piercing bomb hit forecastle by No. 2 turret, which it is believed penetrated to the black powder magazines, setting off the smokeless powder magazines adjacent and causing the explosion which destroyed the ship forward" (Geiselman 1941) In a later assessment after extensive diving operation on the ship, including an attempt to investigate the path of entry of this bomb, the Commandant of the Pearl Harbor Navy Yard stated that the bomb was reported to have struck the ship near turret No. 2. However, his speculation based on the greater structural damage forward of turret No1, particularly on the port side, was that the bomb may have penetrated on the port side (Paine 1943:2).

In order to model the detonation of the forward magazines and its impact on the hull, an estimate of the munitions contained in the forward portion of the hull is necessary. In the 1913 specifications for No. 39, later BB 39, USS *Arizona*, ammunition stowage requirements (Navy Department 1913:210-212) listed 1,300 14-in. amour piercing projectiles, at 1,410 lbs. apiece. The stowage required for the 14-in. powder charges, smokeless powder packed in 500-lb. powder tanks, was for 1,300 powder charges, or 250 lbs. of powder for each projectile. There is no listing for 14-in. explosive charges to initiate the smokeless powder, although they would be required. The 1913 specifications call for stowage for 5,000 40-lb. tanks of 5-in. powder for 5,000 5-in. projectiles and for 3,400 lbs. of saluting powder, assumed to be black powder, packed in 17 200-lb. powder tanks. In 1916, *Arizona* carried 22 5-in. guns, in 1941, 18 were carried (Lott 1978:51).

In analyzing the forward magazine explosion, Lott (1978:43) quotes from an October 1943 letter that *Arizona* had on board its full complement of smokeless powder in six magazines between frames 31 and 48 on the first platform (Figures 3.2 and 3.3). There was also 1,075 lbs. of black powder in the black powder magazine, which was also stowed on the first platform, centerline between frames 37–39 (Figure 3.2) between the six smokeless powder magazines. Close to the black powder magazine is the small arms locker (Figure 3.2).

The only document located that discusses the amount of powder in the forward magazines was by R. W. Paine, Commandant of the Pearl Harbor Navy Yard (Paine 1943:2-3) His account was developed from conversations with personnel attached to the ship at the time of the attack:

> (1) 308 – 14” shells in each turret, Nos. 1 and 2, on turret shell decks and in handling rooms, 1st platform.
> (2) 616 cans of smokeless powder for each turret, Nos. 1 and 2, distributed in six accommodating magazines, A-424-M, A-420-M, A-414-M, A-13-M, A-421-M and A-423-M 1st platform.
> (3) 25 – 25# cans and 150 – 3# charges of black powder between Nos. 1 and 2 turrets in the black powder magazine A-415-Mm 1st platform.
> (4) 3,400 cans of 5” – 51 caliber smokeless powder in the 5” magazines forward. Powder about equally distributed between magazines on 1st and 2nd platforms, A-432-M, A-431-M and A-324-M.
> (5) Approximately 300,000 rounds 50 caliber AA ammunition in forward 50

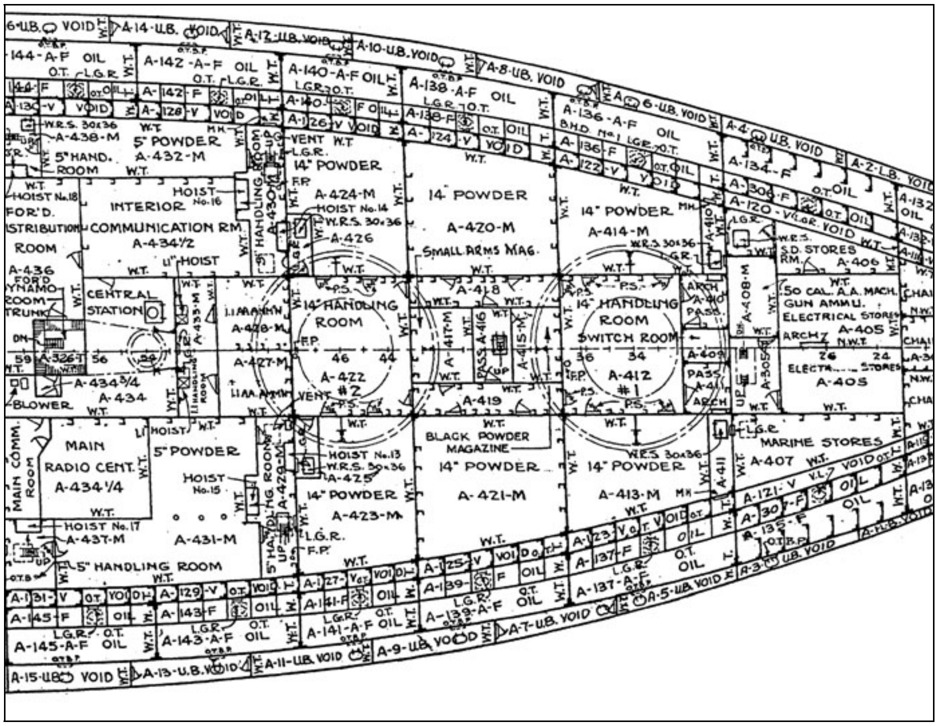

Figure 3.2. *Arizona* blueprint of forward magazines on first platform deck (USS *Arizona* Memorial Archives).

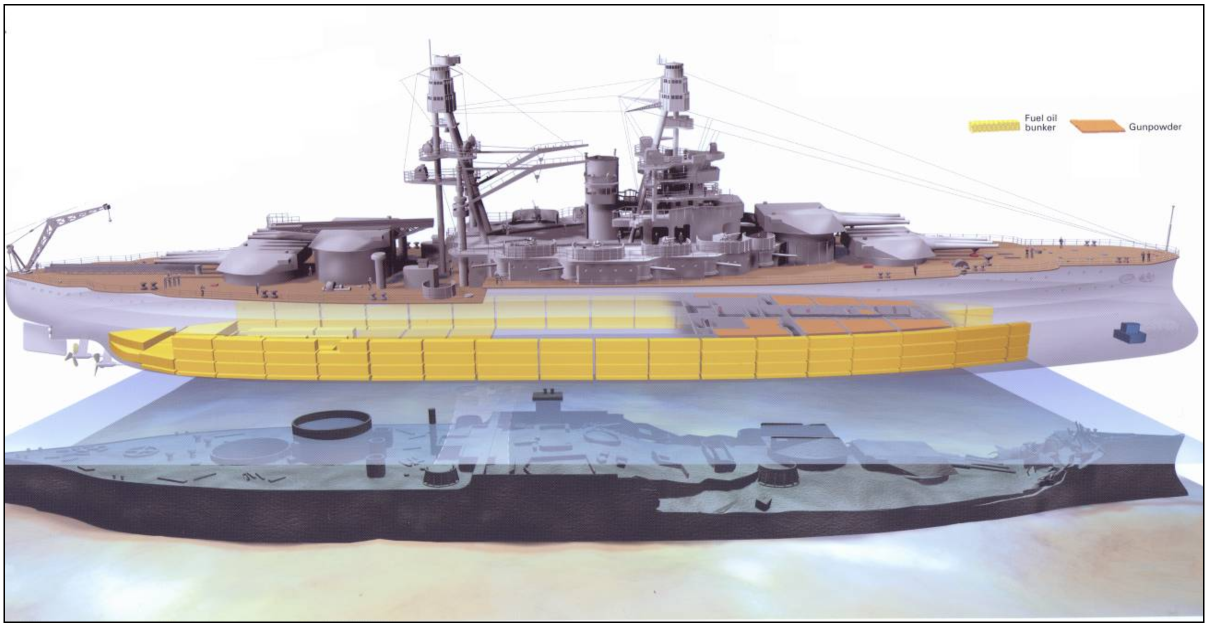

Figure 3.3. Graphic of *Arizona* showing oil bunker and forward magazine locations in relation to hull damage mapped by SRC in the 1980s (Graphic by National Geographic Society).

caliber magazine, A-408-M.

(6) Approximately 3,500 – 5” 51 caliber projectiles in ammunition passages amidships, B-504-m and B-505-M, 3rd deck.

(7) Small arms ammunition, approximately 100,000 rounds of 30 caliber, 5,000 rounds of 45 caliber, and 1,000 service primers, in A-417-m, 1st platform.

(8) 75 – 14” Primers in each turret, Nos. 1 and 2, gun chamber

(9) 50 electrical detonators in trunk A-511-2-T, third deck.

In the *Arizona* ballistic data supplied by Lott (1978:51), 14-in. firing charges for 1941 were 420 lbs., each requiring a 31.5-lb. explosive charge and primer. *Arizona* was carrying 616 shells and “616 cans of smokeless powder.” The weight of 14-in. powder cans is not given by Paine, but they must have minimally been 420 lbs. for a total of 258,720 lbs. or 129.4 tons of smokeless powder in the forward magazines and 19,404 lbs. or 9.7 tons of explosive charge and an unknown number of primers for a total of 139.1 tons of 14-in. powder in the forward magazines. Paine (1943) reported 1,075 lbs. of black powder in 25 25-lb. cans and 150 3-lb. cans.

Originally, *Arizona* mounted 22 5-in./51 caliber guns, and specified 5,000 rounds. In 1941, these guns were reduced to 10 with 8 5-in./25 caliber dual purpose guns added (Lott 1978:30), giving a total of 18 5-in. guns. Each 5-in. round required about 25 lbs. of powder and a 2-lb. explosive charge (Lott 1978:51). Paine does not give the weight of the 1941 5-in. powder cans, but in the 1913 *Arizona* stowage weight specifications (Navy Department 1913:211) it lists these cans as 40 lbs. Lott (1978) indicates 5-in./51 caliber guns required a 24.5-lb. firing charge and a 2.04-lb. explosive charge per shot. Assuming the 3,500 5-in. powder cans were 40 lbs., there would have been 140,000 lbs. of 5-in. powder, or 70 tons. This is sufficient for 5,714 5-in. rounds, which would require 11,657 2.04-lb. explosive charges. Paine (1943) does not mention these charges in his listing, but there would have been sufficient explosive charges to fire each round, which adds another 23,780 lbs. or 11.9 tons of powder for an estimated total of 81.9 tons of 5-in. explosives stored in the three forward 5-in. magazines.

In addition to the large gun munitions, there were 100,000 50-caliber rounds and 6,000 rounds of small arms ammunition located in the small arms magazine forward on the first platform. A .50 caliber powder charge is about 230 grains or about one-half ounce of powder, for a total powder weight for the .50 caliber ammunition of 3,125 lbs. or 1.6 tons of powder. Cumulatively, we estimate there was minimally about 222.6 tons of powder involved in the detonation of the forward magazines, primarily 14-in. and 5-in. smokeless powder and primary explosive.

There is no question that the smokeless powder in the forward six magazines were sympathetically detonated, either by the armor piercing 700 kg bomb's 70-lb. bursting charge or by a topside fire setting off the black powder magazine, which in turn detonated the smokeless powder. The actual detonation chain will likely never be known, and there are several theories, some still actively debated, about what occurred (for example, see Stillwell 1991:274-278). In any case, the detonation of the forward munitions, however devastating, was incomplete. Five-in./51 caliber powder cans were found on Ford Island 350–400 ft. off *Arizona*'s starboard side (Lott 1978:43); unburned 14-in powder grains were found on the quarterdeck of the USS *Tennessee* moored forward of *Arizona*, a distance of 400 ft. and 500 ft. from shore on Ford Island, a distance of 900 ft.; exploded 5-in. powder cans were found along the beach on Ford Island a distance of 350-400 ft., (Paine 1943:4); and 50-caliber rounds remain in the forward bow area.

Paine (1943:3) described the forward magazine explosion:

> It appears the explosion in the forward magazines was vented through the sides of the ship from about Fr. 10 to about FR. 70 and upward through the decks forward of turret #1. Due to the general extent of interior damage between Frs. 10 and 70, it is difficult to determine the exact magazines in which high order detonation took place, although the more severe damage is between about Frs. 10 and 33.

USS *ARIZONA* BATTLE DAMAGE

By the afternoon of December 7, USS *Arizona* was determined to be a total loss. The Navy Yard's Planning Section was informed that *Arizona* was: "broken in half and burning. Completely submerged except for the two aft turrets and tripod mast. No job orders issued" (Summary of Damage Reported to Planning Section, Dec. 7, 941), which indicated nothing could be done for the ship. In a memorandum from USS *Pennsylvania*, the flagship, sent by Cmdr, Homer N. Wallin, Battle Force Material Officer, at 1345 December 7, he states: "The *Arizona* is a total wreck, she is resting on the bottom without much list, and is still burning forward. The foremast has fallen forward about 45°" (Wallin 1941:1)(Figures 3.4 and 3.5). *Arizona*'s hull was reported to have settled for days (Madsen 2003:81), releasing air bubbles from the interior. In Memorandum No. 7, December 9, 1941, from the United States Pacific Fleet Battle Force, USS *California*, Flagship, *Arizona* and *West Virginia* were declared "total wrecks" (p.3).

By December 28, 1942, in a memo from Commander Base Force to Commander in Chief, Pacific Fleet (Commander Base Force to Commander in Chief, Pacific Fleet December28, 1941:6-7), the assessment of *Arizona* was:

Figure 3.4. *Arizona* burning, forward mast toppled, December 8, 1941 (USS *Arizona* Memorial Photo Archives).

Figure 3.5. *Arizona* damage soon after fires were extinguished December 10, 1941 (USS *Arizona* Memorial Photo Archives).

> This ship is damaged by enemy action, internal explosions and fire to such and extent as to be valueless except as to the material in the after 40% of length not damaged by immersion in sea water, and as an expensive source of steel scrap. Subject to further diving surveys, it is recommended that work on this ship be limited to removing No. 3 and 4 turrets as practicable with local weight handling equipment and removing other useable material under other Bureaus and to cutting off, as opportunity affords, of the damaged structure above water.

COMPILATION OF *ARIZONA* BATTLE DAMAGE BY FRAME

Frames 10-70: Most forward interior damage between these frames (Paine 1943:3).

Frames 10-33: the more severe damage is between these frames (Paine 1943:3).

Frame 30: Investigations by salvage divers revealed that the hull bottom had a major crack about 120 ft. from the bow [frame 30]. Divers used water jets and pumps to tunnel beneath the hull to ascertain damage from bow back to frame 78. There was no other damage observed (Raymer 1996:86-91).

Frame 35: Torpedo hit reported by eyewitnesses. This will be discussed below with the "bomb down the stack" observation that was reported at the time.

Bomb Down Stack: Reported by eyewitnesses and in various reports, and discussed below in more detail below.

Bomb that sympathetically detonated forward magazine: Apparently, one large, possibly 2,000-lb., armor-piercing bomb hit the forecastle near No. 2 turret, which it is believed penetrated to the black powder magazines, setting off the smokeless powder magazines adjacent and causing the explosion which destroyed this ship forward (Geiselman 1941:2; Homann 1942a:2). Although divers attempted to investigate the path of entry of this bomb through the ship, extensive damage made it impracticable. "It appears probable, due to the greater structural damage forward of turret #1, especially on the port side, that the bomb may have penetrated on the port side of turret #1" (Paine 1943:2).

Frame 66: "One bomb hit, size of bomb not known, on boat deck at frame 66, port side, by No.4 antiaircraft gun ammunition hoist, extent of damage done by this bomb is not known" (Geiselman 1941:2; Homann 1942a:2).

Frame 67: "One bomb approximately 1000-lb., hit on boat deck just forward of stack, at frame 67. Width of hole on boat deck is approximately four feet, depth of penetration is not known" (Homann 1942a;1; Geiselman 1941:). This is also listed by McClung (McClung n.d.:1).

Frame 70: The decks have collapsed and slope downward from about frame 70 to about frame 34. Between frames 45 and 34, the upper deck is about 3 ft. the top of the armor on the starboard and at the top of the armor belt on the port side (Paine 1943:5).

Frame 73: "One heavy bomb hit, estimated over 1,000-lb., port side of boat deck just forward of the incinerator, by No. 6 antiaircraft gun. The extent of damage done by this bomb is not known" (Geiselman 1941:2; Homann 1942a:2). This is also listed by McClung (McClung n.d.:1).

Frame 76: Interior damage prevented divers from penetrating further than frame 76 on the main and second decks and not forward of bulkhead 78 below the third deck. However, on the third deck in ammunition passageways A-504-M and A-505-M access was possible as far forward as frame 66. In these spaces the second deck sloped down forward and the third deck was split and blown upward. No access could be gained to the firemen's passage C-501 on the third deck (Paine 1943:5).

Frame 78: "The whole ship forward of frame 78 (after fire room bulkhead) is badly damaged." … "It is not possible for divers to operate inside of the vessel forward of frame 78 due to the very extensive wreckage up to and including the main deck." … "It is believed that all of the vessel aft of frame 78 is floatable, or could be made floatable." … "Construction of a sheet pile cofferdam is not practicable on account of the porosity of the coral" … " the after portion of the vessel could probably be floated satisfactorily" (Furlong July 24, 1942:2). See also Paine October 7 1943 memo, which also discusses damage forward of frame 78.

Frame 78-90: A bomb hole was discovered on the second deck between frames 78 and 90 on the port side. A diver traced its path down two decks to where it was located in the walk-in meat freezer (Raymer 1996:76). This bomb hole is depicted in Figure 3.6.

Frame 85: One 500-lb. bomb hit the port gallery deck. The width of the hole in the deck is approximately 24-in. in diameter, with the depth of penetration unknown (Geiselman 1941:1; Homann 1942a:1). This is also listed by McClung (n.d.:1).

Frame 96: One 500 or 1000-lb. bomb hit the port side of the quarterdeck in M.B. Stowage, with a 24-in. hole in the deck and penetration unknown (Geiselman 1941:1; Davison 1941; Homann 1942a:1). This is also listed by McClung (McClung n.d.:1).

Frame 120: Some bomb damage and fire, starboard side (Commandant, Navy Yard, PH to Chief of Bureau of Ships, March 15, 1942).

Frame 123: 500-lb. bomb hit the face of turret No. 4 on the starboard side, glanced off and passed through the deck at frame 123, starboard side of the quarterdeck, between the captain's hatch and No. 4 turret and exploded in the captain's pantry, destroying both the captain's and admiral's pantry (Geiselman 1941:1; Fuqua 1941; Davison 1941; Miller 1941; Homann 1942:1). McClung (n.d.:1) notes it went "Through the quarterdeck at frame #123 to starboard of No. 4 turret. This bomb exploded in the Captain's pantry" (McClung n.d.:1).

Figure 3.6. Bomb hole, forward of the galley, port side, near frame 78 (NPS Photo by Patrick Smith).

Torpedo: "From the report of the commanding officer of the U.S.S. *Vestal*, which was moored alongside of the *Arizona* to port, bow to stern, the USS *Arizona* apparently sustained a torpedo hit about frame 35, port side. Damage caused by this torpedo hit cannot be determined, as the ship in this area has been completely destroyed. The outboard fuel oil tanks were filled to ninety-five percent capacity in the area of the possible torpedo hit" (Homann 1942a:2). Indications are that this statement originated from the interview that Homann conducted with Lt. CMDR S.G. Fuqua in December 1941 (Fuqua 1941:2).

During hull damage surveys, divers could find no evidence of torpedo damage above the mudline (McClung n.d.:1). Paine (1943:3), after extensive investigation of *Arizona*'s hull noted that "no evidence of torpedo hits has been found, although the condition of the flat bottom forward inboard … is not known. The bottom structure in the forward part of the ship is not accessible from inside and is embedded in the mud outside." The ship had not sunk to stable sediments at that time, so likely there was more hull exposed "above the mudline" when initially inspected than when the ship later reached stability. In the 1980s, NPS divers and U.S. Navy Mobile Diving and Salvage Unit One divers conducted an extensive survey of the portside above and below the mudline with water jet probes to locate possible torpedo damage. Probing along the hull in this area produced negative results. To conclusively determine whether a torpedo hit in this area would require extensive excavation below the mudline.

Bomb Down the Stack: Some eyewitness report a bomb going down the stack. Lt. A. J. Homann, who later became acting *Arizona* commander, personally interviewed and certified several *Arizona* survivors within a couple weeks of the attack. William W. Parker, *Arizona* survivor, reported,

> One bomb hit in front of the forward turret. We think it went down the magazine, for the whole forward part of the ship blew up and caught fire. Myself, and one of the other men must have gotten blowed over the side of the galley deck. About that time, a bomb went down the stack (Parker 1941).

Apparently, Acting *Arizona* Commander E. H. Geiselman (1942:2) made the first official recording of a bomb going down the stack in his December 17, 1941 damage report. He reported a heavy bomb, 1,000 or 2,000 lbs. had gone down the stack.

Acting *Arizona* Commander Homann (1942a:2, 1942b:2) who relied on survivors' interviews states in correspondence to the Chief, Naval Operations that "an early bomb hit down the stack and disrupted the fire main and bilge pumps." This is also listed by McClung in a report to the Salvage Engineer (McClung n.d.:1). One of the survivors was Lt CMDR S.G. Fuqua, who reported a bomb had gone down the stack, and that it was not known "whether a torpedo hit the face plate of No. 4 turret indirectly" (Fuqua 1941:2). Divers investigating the uptake armor grating in the main deck as far as the wreckage would permit, and the grating was believed to be intact (Paine 1943:5), indicating no bomb went down the stack. Again, like the search for torpedo damage, no damage has been observed by NPS or Navy divers in the deck area around the stack. Based on material evidence, a bomb did not go down the stack and the fire pumps were disabled by the magazine explosion (Figure 3.7).

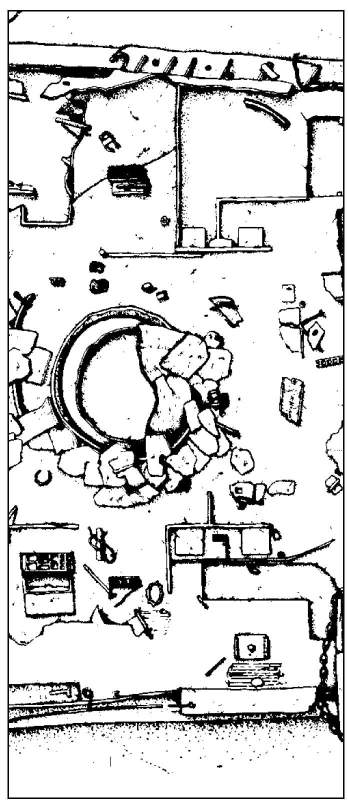

Figure 3.7. Detail of archeological map of *Arizona* depicting the stack area, with bow to the left (Drawing by NPS-SRC).

RESULTS OF COMPREHENSIVE HULL DAMAGE SURVEY

Lt. M. L. McClung (n.d.:2-4), serving as Assistant Salvage Engineer, provided an extensive damage report to the Salvage Engineer. This report, based on diver hull surveys, provides a complete picture of *Arizona*'s condition soon after the attack:

> 6. A survey of the port side of the ship indicates that aft of frame #70 the hull is intact. Forward of frame #70 the plating on the topside of the blister is pulled away from the ship practically all of the distance to frame #18. The hull above the blister is damaged by explosion from frame #67 forward to a crack from the gunwale to the blister at frame #22. This area above the blister is bulged and blown out so that divers cannot walk on the flat top of the blister. From frame #22 forward the damages lessens until the bow and bow and stem are in fair condition forward of frame #12.
>
> 7. The starboard side of the ship shows a condition very similar to the port side. Aft of frame #76 the hull is reported by the divers as intact with no apparent damage. Forward of frame #76 and reaching to frame #72 the rivets in the hull are loose. At frame #72 the blister is cracked from the top down to and below the mud line as far as divers could reach without extensive excavation. The blister is pulled away from the hull. The hull is blown out and torn in a manner similar to that on the port side. This damage reaches to frame #22, then diminishes leaving the bow intact [Figure 3.8 and Figure 3.9].
>
> 8. The top hamper of the vessel is burned and buckled to render it useless as anything except scrap.
>
> 9. The upper deck forward of No. 2 turret is blown out. The deck has been folded outward and forward so that divers descend thirty feet before striking wreckage which is in such a condition as to prevent inspection.
>
> 10. The main deck aft of the break to the upper deck at frame #88 is in good condition with exception of one large hole, 4' by 6' athwart-ship made by the bomb which glanced from the starboard side of No. 4 turret and ten small holes ranging from 5 to 12 inches in diameter within fifteen feet of the

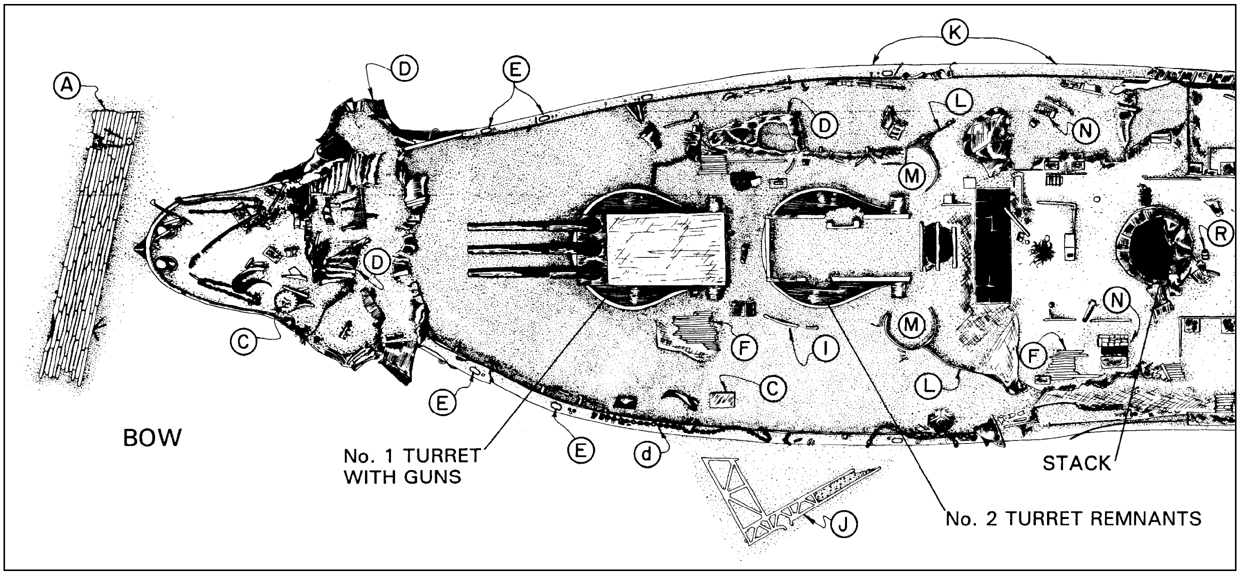

Figure 3.8. Planimetric view of *Arizona* bow damage (Drawing by NPS-SRC).

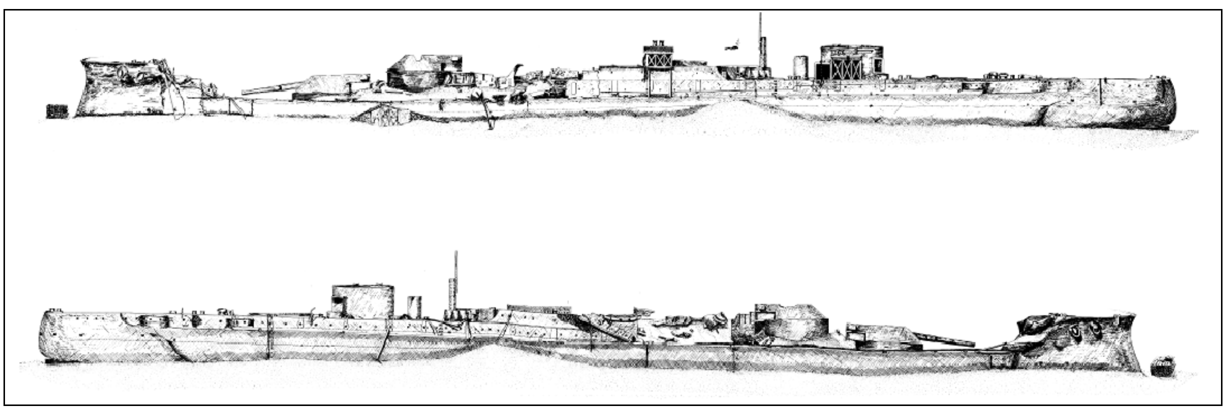

Figure 3.9. *Arizona* profile views port and starboard depicting current condition (Drawing by NPS-SRC).

large hole. Forward of frame #88 the main deck is buckled and twisted as are all bulkheads and partitions, as previously mentioned. The 5 in. batteries on each side of the deck are burned so as to render the guns useless. The ship's divers have tried to explore this part of the ship but have been unable to do so on account of the twisted and broken condition.

11. The ship's divers have removed valuables from the upper and lower Ward-room country. This part of the ship is in good condition with exception of the area damaged by fire and by the bombs which struck near No.4 turret. Between frames #76 and #90 the rooms on the starboard side consisting of the Captain's office, Engineer's office and Disbursing office have been explored and the valuables removed. The center of the ship in this area is a twisted mass of wreckage. The area astern of frame #90 on the starboard side consisting of Junior Officer's staterooms was damaged considerably by fire. The Warrant Officers staterooms on the port side were damaged also by fire. The Captain's cabin, Captain's pantry and wardroom and Officer's stateroom were damaged considerably by the bomb.

12. On the splinter deck the only part explored is the lower wardroom and Officer's quarters. This part of the ship is reported as in good condition.

13. A summary of the condition of the ship is as follows: the top hamper with the exception of the main mast and boat cranes forward of frame #88, is burned and blown to a degree, which renders it useless, the upper, main and splinter decks forward of frame #88 are burned and twisted so that they are not safe for exploration by divers. The forecastle is gone and from all divers' reports the part of the ship below the forecastle is blown and twisted similar to that part which is visible. The portion of the ship aft of frame #88 is in fair condition with exception of the portion damaged by bomb hits and fire.

The hull of the ship is apparently in good condition aft of the forward engine room bulkhead and the sides are reported as good aft of frame #76 on the starboard side and frame #67 on the port side. The condition of the interior of the ship aft of the points mentioned is not known. The guns in No. 3 and No. 4 turrets have been removed. The condition of the guns in No.1 and No.2

turrets is not known as these are under water.

14. The soundings taken before and after Dec. 7, 1941, indicate that mud has been deposited on both sides of the ship abeam of turrets No.1 and No. 2. A reasonable opinion of the cause of this deposit based on experience in submarine rock excavation is that this deposit came from under the ship or the water displaced by the explosion brought the mud when it returned.

PEARL HARBOR SALVAGE

SALVAGE ORGANIZATION AND OPERATIONS

The U.S. Navy formed the Base Force Salvage Organization in the week following the December 7, 1941 attack. Commander James M. Steele, commanding officer of *Utah*, was its first commanding officer. Its goal was a simple one: "to deliver ships and equipment to the Navy Yard for disposition. This was a major undertaking; Pearl Harbor was a ship repair facility, not a salvage unit" (Madsen 2003:36).

Navy salvage beginnings can be traced to 1939 with the hastily organized group at the San Diego Navy Salvage Base (Bartholomew 1990:53). The first trained salvage personnel arrived in Pearl Harbor in early January 1941. A group of six officers and 62 enlisted men who were members of the Navy's first formal salvage school arrived at Pearl Harbor. The school had not been held and these personnel had not yet been trained; instead the class would receive on the job training at Pearl Harbor (Madsen 2003:115; Bartholomew 1990:83).

Several conditions led to the rapid salvage and recovery of stricken vessels in Pearl Harbor. The first is that the damage inflicted, although severe, was not as bad as it could have been. The attack had been directed toward capital ships. Of the 86 ships in Pearl Harbor December 7, 1941, 10 were damaged and 9 sunk (Wallin 1946:1). The Navy Yard and personnel were intact, and there was local industrial support available on Oahu. In addition, there were two contractors, one of which was already involved with Navy operations: Pacific Bridge Company in Hawaii working with underwater concrete, and Merritt-Chapman and Scott, which went under contract with the Navy December 11, 1941 to provide services, material and logistical support for salvage operations (Bartholomew 1990:57-59, 69). In addition, divers were immediately available at Pearl Harbor from the Navy Yard, Pacific Bridge Company and the two submarine rescue vessels Widgeon and Ortolan (Raymer 1996:29), the Destroyer Repair Units and the submarine base. In all, about a hundred divers were available (Wallin 1946:30). During the Pearl Harbor salvage operation, nearly 20,000 diving hours were conducted by Navy and contract divers with no Navy casualties and only one contractor casualty (Bartholomew 1990:68). Although Wallin's estimate of the diving hours is somewhat less; he reported 3,000 dives and 9,000 diving hours, mostly on *Oglala*, *West Virginia*, *Nevada*, *California* and *Oklahoma* (Wallin 1946:30). It is likely that the estimate of 20,000 hours is more accurate. Lt. Commander H.E. “Pappy” Haynes, who served as dive officer during the salvage operations, reported 2,299 dives with a total dive time of 7,893 hours for *Arizona* work.

Initial salvage operations were directed to putting out the raging fires, followed by actions to keep vessels afloat and prevent capsizing. Immediately following were evaluation dives to ascertain hull damage sustained during the attack. The final task was to patch and refloat the vessels so they could be transported for more complete repair and restored to service. In the case of *Arizona*, there was never serious consideration of raising the severely damaged hull; salvage work was directed to recovery of useful materials, weapons and munitions. During the remarkable salvage operation at Pearl Harbor, all but three of the damaged and sunk vessels were returned to wartime service.

USS *ARIZONA* SALVAGE OPERATIONS

Initial salvage diving on *Arizona* began December 8, 1941, while the ship was still burning. The first dives were conducted by *Arizona* personnel, and their diving continued through April 1942. These dives were made to recover government funds, confidential publications, official records, personal effects, and ordnance equipment (Haynes 1943: 3).

One of the first salvage dives into USS *Arizona*’s interior took place January 12, 1942 by Cmdr. Edward Raymer, who had served aboard *Vestal*. (Raymer 1996:1-6). The diver entered the trunk hatch near the stern and proceeded to the general workshop (machine shop) on the third deck to investigate a hole beneath the mudline on the port stern discovered during the earlier external hull survey. Originally believed to have been made by a torpedo that had not exploded, Raymer discovered it was a bomb constructed from a large caliber artillery shell to which fins had been welded.

As mentioned, there was no plan to salvage *Arizona* and return it to the fleet. “Salvage” in the case of *Arizona* meant stripping useable materials from the ship. Weapons and ammunition were the top priority. There was no salvage work on *Arizona* from December 30 to January 6, when ammunition removal began (Madsen 2003:113). By January 25, 1942, considerable material had been removed from *Arizona* (Figures 3.10 and 3.11).

Salvage work started on removal of the aft turrets (Progress of Salvage Work, January 25, 1942). A memorandum to file by the Commander Battle Force US Pacific Fleet, January 29, 1942 reporting attack damage stated of *Arizona*, “the ship is considered to be a total wreck except for the material which can be salvaged and reassigned. A considerable amount of ordnance material has already been removed, and work is underway in removing the 12-in. [sic] guns from turrets three and four” (Commander Battle Force January 29, 1942).

The right gun of turret 3 was lifted clear on February 10, 1942. Both turret 3 and 4 were turned 90° to face Ford Island so work could be done (Madsen 2003:139). At that time, the quaterdeck was submerged beneath 10 ft. of water, so a cofferdam was constructed. All three

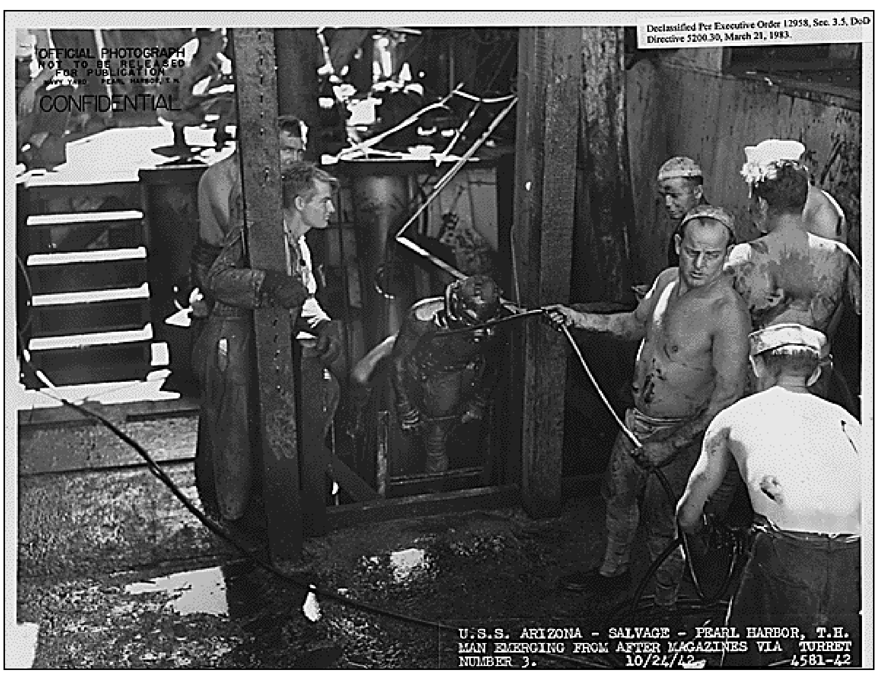

Figure 3.10. Diver emerging from after magazine through turret No. 3 (USS *Arizona* Memorial Archive Photo).

Figure 3.11. Diver on *Arizona* deck, 1943. Note shallow water diving equipment made from gas mask (USS *Arizona* Memorial Archive Photo).

guns were removed in a week. Removal of the 14-in. shells was going on concurrently through February and into March. The broadside guns had been removed and part of the boat deck was cut away for access to guns 5 and 6 (Madsen 2003:173). The foremast was cut away and removed May 6, 1942, the main mast August 23. The guns from turret 3 and 4 were transferred to the Army for use as shore batteries. Guns of turret 2 were removed in September. Boat cranes and kingposts were removed at this time and much of the wrecked superstructure was removed to Waipio Point (Madsen 2003:218). The final work on *Arizona* was completed October 13, 1943. The entry in the *Salvage Diary* for that date stated, "Continued removal of machinery and equipment incident to discontinuance of salvage operations" (*Salvage Diary, Pearl Harbor* ,October 12, 1943).

A bomb hole was discovered on the main deck between frames 78 and 90, and a diver traced its path for two decks. The bomb was located in the walk-in meat freezer. The bomb was recovered and it was identified as a U.S. 15-in. coastal artillery shell still containing the U.S. imprint on the shell's base. Apparently, the U.S. had sold the obsolete shell to the Japanese as scrap metal. They had made a bomb out of the shell, and like the one located in the machine shop, had welded metal fins to it. This shell was transported to the Bureau of Ordnance in Washington D.C. for examination (Raymer 1996:76).

Arizona salvage plans were being revised in February 1942, and its salvage remained a low priority. Consideration was being given to removal of the stricken hull. "It is possible that the after part of the ship can be floated, and raised, but this no doubt involves cutting off of the forward by dynamite. The study of the Arizona project will be undertaken when more urgent work is out of the way (Wallin, February 8, 1942:3).

A month later, Commandant of the Navy Yard, William Furlong reported to the Chief, Bureau of Ships that:

> The *Arizona* is resting on a comparatively solid bottom in berth F-7 with the water level about ten feet above the quarter-deck. The after half of the vessel is fairly intact except internally in way of some bomb damage and fire in the neighborhood of frame 120 on the starboard side [Furlong March 15 1942:1-3].

In this same report (Furlong March 15, 1942), torpedo damage is reported and alternative salvage plans are offered, including mention of a cofferdam:

> 4. Based on damage reports and inspection of the hull below water, it appears that the vessel was struck by one torpedo on the port side at about frame 35 and by seven bombs in various locations. Due to a magazine explosion forward, the whole area forward of the smoke stack is badly wrecked and burned and the hull appears to be generally opened up below the present water line. In view of the great extent of serious damage in the forward part of the ship, it appears impracticable to float the vessel, although floatability could possibly be obtained if a cellular sheet piling cofferdam were driven around the ship….Sufficient sheet piling and equipment for diving are here for this cofferdam. An alternative would

> be to cut up by acetylene burning the whole forward part of the vessel within the cofferdam and to float the after part of the vessel to shallow water for scraping. This amount of work would cost perhaps a half million dollars, [about $6.6 million in 2008 dollars], but would provide a large amount of needed scrap material.
>
> 5. As an alternative to proceeding as above to remove the Arizona from her berth, it is suggested that she be left in her present location but that all visible wreckage be removed and cut up for scrap. All the structure of the ship above the boat deck can be removed and reduced to scrap at a moderate cost without adverse effect to other work….Considerable material and ordnance have already been salvaged. This plan includes the construction of a battleship berth alongside and outboard of the Arizona. It would be possible in time to fit turret No. 3 as a fixed battery in connection with her remaining at her present berth.

BODY RECOVERY

Mounting pressure from Congress for recovery of the remains of *Arizona* casualties led to body recovery operations a few months after the attack. Many bodies had been reported afloat in the machine shop area. Salvage divers recovered approximately 45 bodies from the third deck workshop via the trunk. The advanced state of decomposition precluded intact recovery and identification; the recovery operation was soon halted (Raymer 1996:84, Madsen 2003:173). Additional bodies and skeletal remains were encountered during the salvage operations. These were removed to the hospital, and apparently no further identifications were made. William H.Furlong, Commandant of the Pearl Harbor Navy Yard, in a memo to the Vice Chief of Naval Operations (Furlong july 24 1942:4) estimated there were 900 bodies remaining aboard *Arizona*.

It is likely that USS *Shaw* was the first ship to honor *Arizona* with a standing honor guard. As it passed the sunken hull, it mounted an honor guard at the rail as it passed Arizona on its way to Mare Island February 8, 1942 (Raymer 1996:85, Madsen 2003: 129-130). Capital ships have carried the tradition of honoring *Arizona* as they pass by to this day.

USS *ARIZONA* SALVAGE ACTIVITIES: *SALVAGE DIARY, PEARL HARBOR*, 1943

This compilation of selections from the Pearl Harbor Salvage Diary (*Salvage Diary, Pearl Harbor* 1943) was chosen because each offers something relevant about *Arizona*'s salvage. As discussed above, very soon after the attack, the decision was clear: there would be no attempt to refloat *Arizona*; only usable materials and scrap, mostly superstructure, were to be recovered—anything useful was to be reconditioned and returned to fleet operations. Salvage operations focused on turrets 2, 3 and 4, the 5-in. broadside battery and anti-aircraft guns and ammunition.

During salvage, the ship was explored and some observations regarding the condition of the ship's interior were made and recorded in this diary. There are several items recorded in the *Salvage Diary* that are important to the USS *Arizona* Preservation Project. Some examples are: the overhanging sides above the armor belt were burned off; most of the superstructure removal took place forward of Frame 78; during gun removal, turrets 2, 3 and 4 were sealed and dewatered; however, magazine hatches between turret 3 and 4 were removed to allow removal of munitions—these spaces should be accessible for corrosion analysis measurements with the VideoRay ROV. Any salvage diver observations regarding interior spaces are retained below. Many of these observations were considered in planning which section of the hull would be modeled and were utilized during interior explorations with the ROV.

<u>March 27, 1942</u>: Removed deck above broadside gun No.6.

<u>March 30, 1942</u>: Continuing underwater cutting on broadside stand 7.

<u>May 1, 1942</u>: Continuing to cut away wreckage and foremast. Making detailed study of damage to determine whether vessel can be floated. Some evidence of ship's back being broken amidships, this is being checked.

<u>May 18, 1942</u>: Continued with underwater survey and the removal of topside wreckage. It was found that bulkhead 78 is structurally sound from the hold to the third decks.

<u>June 3, 1942</u>: Continued with underwater survey and removal of topside wreckage. Preliminary inspection of port engine room showed no extensive damage. Preparations are being made for the location of an inspection tunnel

under the forward portion of the ship.

June 4, 1942: Continued with underwater survey and removal of topside wreckage. Approximately 100 tons of wreckage have been removed from the starboard side forward.

June 5, 1942: Continued with underwater survey and removal of topside wreckage. A small derrick sooty is being rigged to handle mud siphon for inspection tunnel under forward hull.

June 8, 1942: Continued with underwater survey and removal of topside wreckage. Inspection to date has revealed that center engine room has little or no damage. Continue: preparations for the removal of ammunition from Turret III.

July 3, 1942: Continued with the removal of topside wreckage. Continued with the removal of 14" powder tanks and also work on 5" A.A. guns. The deck in D-410-M seemed to be buckling as the tanks were removed and 4 x 4" shoring is being put in as necessary.

July 5, 1941: Continued with removal of topside wreckage. Work
is also proceeding on the tunneling under the forward part of the ship. Completed shoring up in D-410-M (deck has L buckled nine inches due to pressure from below). Removal of ammunition and work on 5" A.A. guns was also continued.

July 9, 1942: Continued with the removal of topside wreckage. Removal of ammunition and work on 5" A.A.guns was continued. Eighty 14" powder tanks were removed from D-410-M.

July 11, 1942: Continued removing ammunition from D409-M and sent 78 - 14" powder tanks to West Loch. Continued with removal of topside wreckage and on 5" A.A guns.

July 19, 1942: Removal of topside structure and wreckage continued. Handling room of Turret III flooded yesterday afternoon and divers were sent down to investigate. Inspection showed that outboard bulkhead seams of D-405-M opened up. The after-magazine door showed signs of inward pressure.

July 25, 1942: Divers cutting holding down bolts and wreckage to clear 5" guns. Also excavating to continue survey of Arizona bottom below blister, port side. Survey on starboard side completed, found extensive wrinkling of hull plating at turn and just under turn-of-bilge between frames 17 and 19. Continued removal of 14" projectiles from D-407. Sent 40 -14" projectiles to ammunition depot.

July 28, 1942: Continued caulking around water shed of Turret I. Stopped pumps and flooded to close passage way doors.

August 24, 1942: Yard machinist continued working on pump in Turret IV. The pump should be back in commission some time today. Divers continued cutting on starboard 5"/25 gun. Tripod mainmast removed. Ship's bell will be turned over to Public Works for possible use as a PIS alarm.

August 29, 1942: Completed removing 14" powder tanks from D-413-M and D-412-M to shell deck of Turret IV. Removed one body from Turret IV and turned over to medical authorities.

August 30, 1942: Shored up deck in #4 handling room. Making preparations to cut through bulkhead into B-416-M to remove small arms ammunition.

September 4, 1942: Diver completed cutting bulkhead into D-416-M. Diver could not enter magazine due to ammunition boxes.

September 5, 1942: Divers closed armored hatch to D-414. Started pumping magazine area.

September 10, 1942: Continued removing small arms ammunition from D-416- M. Diver continued cutting decks above port broadside gun.

September 12, 1942: Diver closed vents in D-422 1/2-A and D-420-M. Drilled two vent holes in bulkhead between D-416-M and D-422 1/2-M.

September 13, 1942: Diver removed hatch in D-415 to allow room for deep well pump. Flooded magazine area so diver can burn bulkhead between D-416-M, and D-422 1/2-M.

September 16, 1942: Completed removing ammunition from D-422 1/2 - M All ammunition has been removed from the let platform. Diver started checking vents and doors on 2nd platform.

September 20, 1942: Diver finished cutting drain hole in bulkhead. Diver replaced hatch on first platform which was removed to burn a hole in it for the pump pipe. Set up motor unit and frame for deep well pump.

September 22, 1942: Divers continued closing vents on second platform.

Checking all material, machines, etc. in preparation for removing 5" ammunition from second platform.

September 23, 1942: Divers continued closing vents and other openings on 2nd platform. Awaiting crane service to install deep well pump.

September 23, 1942: Divers continued checking vents, doors and other closures. The door leading to D-304-M is sprung and difficult to make tight.

September 30, 1942: Diver burned one drain hole between D-302-M and D-302 1/2-M. Started pumping second platform area [Figure 3.12]. Recovered remains of 8 bodies and sent to area hospital.

October 3, 1942: Continued pumping operations to keep 2nd platform magazines unwatered. Continued removal of debris from 2nd platform magazines. Started making preparations to rig lights. Diver continued working on 5" gun on port side.

October 9, 1942: Continued pumping operations. Started removing catapult charges from D-306 1/2 M. Removed shell carrier and piston from Turret III so as to enlarge mess hole.

October 12, 1942: Continued pumping operations. Continued removing catapult ammunition. Closed 5"1/25 cal. ammunition hoist on 3rd deck to stop leakage from trunk into magazines, and opened door to D-404-M and D-409-M.

October 14, 1942: Started removing 5"/25 cal. ammunition from D-304-M. Continued pumping operations.

October 15, 1942: Continued pumping operations. Continued removing 5"/25 cal. ammunition from D-304 1/2-M.

October 19 1942: Continued pumping operations. Made preparations to start removing 5"/25 cal. Ammunition from D-306-M. Repairing gear, checking lighter, etc. Yard diver continued underwater cutting to remove structural wreckage forward. Recovered one paravane.

November 2, 1942: Continued pumping turret #3. Continued removal of holding down clips, and machinery in turret #3. Yard divers continued cutting scrap steel in forward section of ship. Divers made inspection and took measurements for cofferdam to be installed on main deck at stern for unwatering airplane crane machinery compartments and removal of kingpost and machinery.

Figure 3.12. Pump and platform used to unwater second platform magazines, Space D-307, Frame 119-120, October 5, 1942 (USS *Arizona* Memorial Photo Archive).

November 6, 1942: Continued pumping operations. Completed removal of holding down clips, Turret 3. Continued removal of motors and disassembling train, worm and pinion. Began preparations for removal of top plates, turret #2 and top plates of conning tower. Continued diving operations on aviation crane. Continued cutting of interior wreckage forward for recovery of scrap steel.

November 25, 1942: (1) Continue pumping operations in turrets #3 and #4. Continued removing chains in powder hoists in turret #4. (2) Divers continued cutting underwater scrap forward of frame #78. No scrap metal removed due to lack of crane service. (3) Continued removal of bolts holding roof plates of turret #2. Completed cutting connections of roof plate of conning tower to interior bulkheads. (4) Continued work toward removal of stern airplane crane machinery.

December 4, 1942: (1) Continued pumping operations in turrets #3 and #4, Removed small battery compartment exhaust blower and motor from shell deck, (2) Divers made exploratory dive, attempting to reach handling roan underneath #1 turret. Unable to reach handling room because of wrecked hatch. (3) Continued removal of bolts in roof of conning tower. Continued removing wiring and structure inside of conning tower (4) Divers cutting underwater scrap steel forward of frame #78. None removed.

December 5, 1942: (1) Continued pumping operations in turrets #3 and #4. (2) Divers continued attempts to reach handling room, turret #2 to determine possibility of unwatering turret. They were unable to find a passage to handling room because of wreckage. Continued cutting bulkheads in turret #2. Continued preparing section of key roof plate for removal. (3) Continued preparing roof of conning tower for removal. Drilling out brass holding down bolts. (4) Continued cutting underwater scrap metal for of frame #78. None removed from ship.

December 8, 1942: (1) Continued pumping operations in turrets #3 and #4. (2) Divers continued cutting wing in bulkheads of gun chamber, turret 2. This is moose [loose?] to gain free access to angle joining top and side armor plates. Continued jacking up section of key plate of roof to prepare for lifting. (3) Divers continued cutting underwater scrap metal forward of frame 08. None removed from ship. (4) On stern airplane crane, removed socket bearings of kingpost and pinion Lear on 2nd deck. Started cutting access hole to 3rd deck.

December 9, 1942: (1) Continued pumping operations in Turrets 3 and 4. (2) Divers continued cutting gun chamber bulkheads in Turret 2. Continued removal of section of center plate in roof of Turret 2. (3) Divers continued cutting underwater scrap forward of frame n. No scrap steel removed from ship today. (4) Cutting access hole in 2nd deck aft into D-512-E for removal from 3rd deck of hoisting machinery of stern airplane crane.

January 16, 1943: (1) Continued diving operations on conning tower central tube. Discontinued removal of keys in armor. Expect to lift top half of tube without disassembly (Weight about 100 tons.). Resumed closing bottom of tube for unwatering. Removing hatch at bottom of tube to repair gasket. (2) Continued cutting underwater scrap metal forward of frame #78. Removed some lockers and wreckage. (3) Divers searched for anchors and towing bridle. Towing bridle was previously removed from ship. Anchors were apparently blown clear of ship, and have not been located. (Note: Letter from BuShips has requested information as to possibility of recovering the above items.)

January 21, 1943: (1) Divers removed port shell dumping cradle in gun chamber, turret #2. Began cutting of bulkheads abreast powder hoists to gain access for installation of powder hoist covers. (2) Installed stage in conning tower armored central tube. Removed one 1 1/2"x9" bolt of about 50 bolts joining upper and middle section of tube. (3) Divers continued cutting underwater scrap metal forward of frame #78. None removed from ship. (4) Removed about 900 ft. of 2" wire rope towing cable from reel in D-504. Completed removing 8" manila mooring line from reel at frame #104, starboard side, 2nd deck. Removed considerable amount of 2 1/2" manila line from another reel at same location.

February 1, 1943: (1) Continued operations in turret #2. Divers closing off powder hoists and fitting covers on blower openings in gun pit. (2) Diver continued cutting away structure outside conning tower central tube. (3) Divers continued cutting underwater scrap metal forward of frame #76. None removed from ship.

February 13, 1943: (1) Divers continued installing and making tight covers on gunports, turret #2. Diver worked under wreckage of drip pan overhang of turret and ventilators so that openings in overhang may be closed. (2) Continued pumping in turrets #3 and #4. Expect 150 ton crane to be available to remove turret #3 side armor plates today, after which temporary ventilation will be reinstalled and work started toward removal of at turret. (3) Divers continued cutting underwater scrap metal forward of frame #78. Removed 6 tons of scrap steel and about 30 feet of anchor chain.

February 22, 1943: (1) Continued pumping turret #2. Diver completed plugging ventilation holes in overhang. Manufactured discharge rope and flange for electric deep well pump. Lashed deep well pump together with 10" and 6" gasoline pumps in turret #2. Lowered water level, sufficiently to determine location of several leaks. Divers changed shoring of power hoist covers. (2) Continued pumping turrets #3 and #4. Shipfitters continued clearing area for laying out cut at point where turret #3 is to be separated for lifting, and fitting metal parts to wooden lifting guides. Shipwrights making up and fitting lifting guides. (3) Divers jetted mud from damaged area forward of frame 22, cut underwater wreckage at bulkhead #20, completed freeing center wildcat for removal; continued cutting for removal of conning tower foundation, and continued cutting for removal of wreckage projecting beyond side of ship at frame 66.

February 23, 1943: (1) Divers worked in turret #2 stopping leaks disclosed by lowering of water level by pumping. (2) Shipwrights continued making up and fitting wooden guides to be installed in shell deck, turret #3. Shipfitters and drillers continued fitting metal face pieces on guides. Installed muffler on Diesel engine of pump in turret #4, and continued pumping turrets #3 and #4. (3) Divers recovered center wildcat and about six tons of scrap steel at fr.20.

Continued underwater cutting as follows: damaged bulkheads on 3rd deck at fr. 24, port; bounding angle around conning tower tube; upper deck projecting over side at fr. 66, port; and superstructure deck aft of conning tower, port side.

February 26, 1943: (1) Diver continued closing leaks in turret #2 gun chamber. Water level lowered to approximately 4 ft. from top of side armor. (2) Continued pumping turrets #3 and #4. Installed a 44' electric deep well pump in turret #3. Continued making up lifting guides for turret #3. Clearing space at circle deck for placing shoring to support lower section of turret. Clearing area for laying out cut at point where turret is to be separated. (3) Divers recovered 69 gas masks, Mark III, from compartment d-311. Masks delivered to berth 5 for disposal. (4) Divers jetted mud and silt from wreckage at frame 20, port; cut on wreckage in same area; attempted to lift large section of steel outside ship at fr. 30, starboard ; and cut on wreckage aft of conning tower. About 6 tons of scrap metal removed from ship.

February 28, 1943: (1) Lifted armor plate #T-2 from roof of turret #2. (2) Continued pumping turrets #3 and #4 and installing lifting guides on shell deck. Made preparations for placing shoring on circle deck. Laid out line for cut to separate upper and lower sections of turret. (3) Divers resurveyed section of forecastle deck over starboard bow; cutting on bulkheads on forecastle deck fr.21 port; cutting structure around conning tower central tube and boat deck aft of #2 turret to clear way for later removal of guns from #2 turret; and completed cutting overhanging wreckage at fr.66, port. No scrap removed from ship.

March 1, 1943: (1) Divers continued closing leaks in turret #2. Water level has now been lowered to about 6 ft. by pumping. (2) Continued pumping turrets #3 and #4. Continued installing, lifting guides and placing shoring to support lower section, turret #3. Expect to finish shoring today and begin cutting tomorrow. (3) Divers cutting wreckage in side of ship about fr.20 and aft of conning tower tube about fr.55. Removed and placed on forward quay a piece of scrap weighing about 15 tons with deck winch attached. This piece was over side of ship at fr.30, starboard.

March 2, 1943: (1) Continued pumping in turret #2. Began cutting overhead beams holding forward roof plate. (2) Continued pumping turrets #3 and #4. Continued installation of guides and shoring in turret #3. (3) Diver cutting damaged bulkhead at fr. 20 and cutting wreckage aft of conning tower to fr.62 to clear area for removal of 14" guns in turret #2. (4) Lifted out section of boat deck at fr. 56 port, and placed on forward quay to be cut up for handling with truck.

March 4, 1943: (1) After rearranging 10" hose, resumed pumping turret #2 and burning over head beams holding forward roof plate. (2) Removed upper section of conning tower central tube. (Wt. about 100 tons). (3)Continued installation of guides and shoring in turrets #3 and clearing out handling room for placing shores to circle deck. Continued pumping turrets #3 and #4. (4) Diver Cutting wreckage forward of #1 turret and aft of conning tower to frame #62. Cutting up scrap on forward quay for removal. None removed.

March 10, 1943: (1) Divers opened W.T.D.s from engine room C-1 into shaft alley D-3 and from shaft alley D-1 into shaft alley D-5; opened W.T.D. from engine room C-1 into shaft alley D-1. Divers also checked, from outside of the ship, all the airports on the starboard side of the second deck from frame 70 to frame 106 and found them securely closed. (2) Divers continued installation of airlock extension at frame 105 starboard side for #7 access hole. (3) Cut an access hole into blister C-87-2-V between frame 86 and frame 87 on the starboard side. (4) Continued skimming fuel oil from the various access holes, and also pumped fuel oil from C- 87-F into the Intrepid. (5) Continued pumping gaseous water from #3 and #6 access holes.

March 13, 1943: (1) Diver worked under overhang of turret #2 closing openings which had been overlooked. This work is difficult due to very limited working space. (2) Continued pumping turrets #3 and #4. Began placing shores in handling room and timber guides on shell deck, turret #4. (3) Divers cutting wreckage at fr.20, 3rd deck; aft of turret #2 to fr. 62; and at r.70, starboard; and removing pyrotechnics in C.T. foundation. No scrap removed from ship.

March 14, 1943: (1) Closed openings in overhang of turret #2. Reduced water level to a point below shell table. It is now possible to remove after roof plate, rangefinder, and then remove shell table to clear way for removing 14" guns. Began cutting loose after roof plate. (2) Continued installation of shores and guides in turret #4 and clearing area for cut to separate turret for lifting. Continued pumping turrets #3 and #4. (3) Recovered and delivered to Yard one ship's anchor with about 12 feet of chain. Placed about 30 feet of anchor chain on forward quay. Recovered about tons of scrap steel and placed on forward quay to be cut up for truck handling. None removed from ship. (4) Diver cutting wreckage projecting from side at fr. 24, port.

March 17, 1943: (1) Pumping turret #2. Cutting loose after roof plate. (2) Continued bracing shores in handling room, turret #4. Laid out horizontal cut for separation of turret. Lifting pads for upper sections of turrets #3 and #4 have been delivered to the ship. The 3" diameter bolt holes in the pads are smaller than holes in bulkheads to which pads are to be bolted. Holes must be reamed and bolts fitted. Continued pumping turrets #3 and #4. (3) Divers cutting underwater wreckage at fr. 20 and aft of turret #2. Removed about 8 tons of scrap from ship. Diver caulking around range finder ports, turret #2. (4) Divers continued recovering gas masks from D-311. Delivered 6 dry cans and 3 leaky cans of masks to berth #5.

March 24, 1943: (1) Pumping turret #2 gun chamber. Continued jacking up roof plates and removing shell loading table. (2) Continued pumping turrets #3 and #4. Continued fitting lifting pads and reaming out holes in lifting pads and in bulkheads, and taking measurements for machining of fitted bolts. (3) Continued alteration of supports for deep well pump abreast turret #4. Employed diver for this work. (4) Divers commenced removal of port deck winch abreast turret #3. Divers cutting underwater wreckage at fr. 20, main and 2nd decks, and aft of turret #2. No scrap metal removed from ship.

<u>April 2, 1943</u>: (1) Completed repairs to 10" pump on turret #2 and began installing an additional 10" gasoline pump. (2) Continued pumping turrets #3 and #4. Received and installed five bolts for lifting pads in turrets #4. (3) Divers continued removal of port deck winch, aft. Divers cutting underwater wreckage at fr.17-20, main and 2nd deck and aft of turret#2 to fr.60. No scrap removed from ship. (4) Connecting airlines for divers to compressors on boat deck and installing new volume tank.

<u>April 4, 1943</u>: (1) Completed installation of additional ten-inch pump (gasoline) on turret # 2. Pumped water down to within about four feet of deck in gun pit. Continued removing project loading cable. (2) Continued pumping turrets #3 and #4. Began removing part of temporary mooring abreast turret #3, port side. (3) Removed from ship and delivered to berth #5, one electric motor from port deck winch, aft at six shell transportation slings (14"). Removed one ton scrap. (4) Installed additional electrical power cable from ship overhead line on Ford Island. (Three conductor, #? cable.) (5): Divers cutting underwater wreckage at frame 24-26, second deck and on wreckage aft of turret #4 to frame #66.

<u>April 7, 1943</u>: (1) Pumping turret #2. Began removing shell rammers and rammer motors. (2) Continued pumping operations in turrets #3 and #4 (3) Continued removal of outboard and of temporary quay abreast of #3 turret. (4) Divers burning section of skin of ship projecting outward above armor at fr.19-21. Cutting wreckage amidship at frame16. Cutting wreckage aft at turret #2 and assisting in removal of quay. (5) Divers removing starboard deck winch aft. No scrap metal removed from ship.

<u>April 10, 1943</u>: (1) Pumping turret #2. Began removal of electric winch motor and rammer motors. (2) Continued pumping turrets #3 and #4. Began installation of lifting pads for second lift in turret #3. (3) Continued removal of dolphins abreast turret #3. (4) Divers cutting underwater wreckage projecting from side at fr.19-21,

port, and wreckage aft of turret #2. Recovered approximately 30 feet of anchor chain from mud outside port bow. Diver assisted in removal of dolphins. No scrap removed from ship.

April 17, 1943: (1) Allowed turret #2 to remain flooded. Waiting for concrete in port shell hoist tube to set before pumping down. (2) Completed holding down clips for cofferdam around turret #4 barbette. Began moving equipment from turret #3 in preparation for lifting. (3) Divers jetting mud from wreckage inside bow at frame 20. Cutting wreckage aft or turret #2 down to and including upper deck. No scrap removed from ship.

April 19, 1943: (1) Pumped turret #2. Began removing part of port shell hoist tube and made preparations for pouring concrete in starboard tube. (2) Removed discharge pipe from deep well pump in turret #3. Cast loose pump for removal. The 150 ton crane was not available due to wind above 12 knots. (3) Delivered port deck winch, aft to berth #5 for overhaul. (4) Divers cutting on wreckage aft of turret #2 to upper deck level. No scrap removed from ship.

April 27, 1943: (1) Pumping turret #2. Removed welded covers from side armor bolt heads on starboard side. (2) Continued pumping in turrets #3 and #4. Removed deep well pump from turret #4. (3) Diver continued closing area around fr. #2. inside bow for cutting. Cutting wreckage aft of turret #2 to frame 64 down to and including upper deck. Divers examined sides of ship forward and found projections at frames 10-20, port and starboard.

April 28, 1943: Pumping turret #2 gun chamber. Removed one electric auxiliary projectile hoist motor and one gear box. (2) Diver cutting water shed of turret #4 to free side armor for lifting. (3) Divers cleaning mud and silt from area around frames 20 in side bow. Lifted several sections of wreckage from area at frame 60, upper deck, including one bake oven, unfit for salvage. (4) Removed approximately 6 1/2 tons of scrap from ship.

April 29, 1943: (1) Pumping turret #2. Cleaned out scrap metal from gun chamber. Making preparations for removing counter-balance mechanisms from guns. (2) Diver continued to cut on watershed of turret #4 to prepare side armor for lifting. Diver continued jetting mud from wreckage inside bow at frame 20.

Continued removing scrap from area aft of conning tower. (4) Making up air ejector pipe for tunneling under bow to determine condition of bottom in area of magazine explosion. (5) No scrap metal removed from ship.

May 1, 1943: (1) Pumping turret #2. Removed counter balance mechanism from loft gun. Began to remove same center gun. (2) Diver completed cutting watershed of turret #4. Began clearing barbette of obstructions to allow fitting of cofferdam. Diver continued clearing mud from wreckage around frame 20 inside bow. Cutting section of skin of ship projecting outboard at frame 21, above armor belt. Cutting wreckage aft of turret #2 on upper deck, frame 64. No scrap removed from ship. (3) Continued fabrication of air ejector pipe.

May 3, 1943: (1) Pumping turret #2. Completed removal of counterbalance mechanisms from guns. (2) Removed the 4 side armor plates from turret #4. (3) Diver cutting obstructions from barbette of turret #4 to allow fitting of cofferdam, after removal of upper section of turret. (4) Cutting underwater wreckage aft of #2 turret to fr. 64. on upper deck. No scrap removed from ship.

May 12, 1943: (1) Pumping turrets #3 and #4. Continued cutting to free foundation of turret #4 for removal. (2) Set 10" gasoline pump in turret #2. Shifted 10" gas pump from wood quay to top of turret #2. (3) Began removal of temporary wood quay, F-7-S. (4) Divers cutting wreckage aft of turret #2 on main deck in order to lift upper deck to frame 64. No scrap removed from ship.

May 19, 1943: (1) Continued removal of forward wood quay and pilings. (2) Continued installation of lifting pads in turret #4 on foundation. (3) Made arrangements for installing an additional electric deep well pump in turret #3 in order to further unwater turrets #3 and #4 for removal of eight magazine doors and door frames. (4) Divers continued cutting aft of turret #2 on conning tower structure; continued cutting holes in turret #4 to drain water from area to be cut for lifting foundation.

May 21, 1943: (1) Continued pumping turrets #3 and #4. Completed installation of lifting pads on foundation, turret#4. Continued cutting to free foundation for lifting. (2) Removed four doors from hinges, two at each end of passageways between turrets #3 and #4 on 1st platform. (3) Divers continued cutting on conning tower foundation structure.

May 28, 1943: (1) Removed recoil and counter-recoil nuts from 14" guns in turret #2. (2) Flooded turrets #3 and #4. Opened four magazine doors in #4 handling room and blanked off air vent in D-413-M. Will unwater turret today in order to remove required magazine doors and frames. (1) Pumped to lower water level in turret #2 sufficiently for removal of the differential cylinders from counter-recoil mechanisms on guns. (2) Diver began cutting out magazine door frames in passageways between #3 and #4 turrets, end doors to D-413-M and D-412-M. (3) Divers continued cutting on conning tower foundation.

May 29, 1943: (1) Diver inspected elevating drive shafts in turret #2 to locate point of separation from Waterbury speed gear. (2) Removed 2 magazine doors with powder scuttles and door frames. Delivered to berth #5. (3) Diver removing doors from hinges in #4 handling room, and continued cutting on conning tower foundation. (4) Continued repairs to deep well pump motor in turret #3.

June 3, 1943: (1) Diver continued cutting to free rear plate, turret #2, for removal. (2) Diver continued cutting out magazine door frames, turret #4. Removed from ship three doors with powder passing scuttles and one door frame. (3) Continued cutting scrap steel to be removed from ship.

July 14, 1943: (l) Diver clearing area aft of turret #2 to frame 60 for removal of guns. (2) Diver cleared debris from hatch in bottom of conning tower central tube. The area below this hatch was found to be so chocked with wreckage that the diver could not gain access. Diver began diving on main deck, abreast turret #2, port side, in an attempt to gain access to 1st and 2nd platforms to inspect structural damage.

July 17, 1943: (1) Diver could not find access to 1st platform in forward part of ship due to wreckage. Attempts were made at frames 34, 28 and at frame 6. (2) Continued clearing wreckage aft at turret #2. Completed removal of castings from front plate of turret #2.

July 17, 1943: (1) Discontinued inspection of structural damage in forward part of ship for BuShips. Diver reported that it is impossible to reach magazine area on first and second platforms without extensive underwater cutting. (2) Divers continued clearing area aft of turret #2 and recovered one stamp-canceling machine from Post Office. Used two divers.

July 26, 1943: (1) Removed two magazine doors and frames from turret #3, making a total of eight doors and eight door frames removed from magazines turrets #3 and #4. (2) Suspended operations on this ship pending the availability of the 150-ton floating crane.

August 1, 1943: (1) Resumed operations, since 150 ton crane is expected to be available on 1 August. (2) Began measuring depth of water to top of blister from frame 70 forward. Measurements are taken at 15 foot intervals and will be made on both sides of ship. This is being done to check previous measurements in damage survey.

August 2, 1943: (1) Attempted to lift foundation of turret #4 from underwater, but foundation could not be moved. Plan to reinstall pumps and underwater turrets #3 and #4 to investigate and free foundation for lifting.(2) Completed soundings to top of blister from frame 75 forward.

August 4, 1943: (1) Divers removed cover from hatch at frames 119-120 in 1st platform and replaced after pump access hole in hatch had been closed by a welded patch. (2) Manufactured cover plate for ventilation opening in compartment D-142-M, in preparation for unwatering turrets #3 and #4. (3) Diver took soundings port and starboard, to the top of the blower at the after end.

August 5, 1943: (1) Removed center 14" gun of turret #2. MkVIII, Mod.4, #18L3 from under water. Gun was placed on deck of 150 ton crane, breech opened by hand and entire gun sprayed with Tectyl. The powder chamber contained a fourteen inch drill projectile and a brass backing out slug. Used two divers to assist riggers.

August 6, 1943: (1) Diver completed securing W. T. hatch leading to D-307 and installed cover plates on exhaust vents in D-412-M and D-413-M. This work is in preparation for unwatering turret #4.

August 21, 1943: (1) Began installation of pumps on turret #2. (2) Divers commenced taking soundings of various points on ship for use in completing sketch plan of condition of the ship.

August 24, 1943: (1) Continued the installation of pumps for the unwatering of the gun chamber of #2 turret. Utilized the services of divers as necessary. (2) Took elevation of various parts of the ship in order to determine its present position.

October 11, 1943: (1) Diver continued cutting off deck lug holding down bolts in turret #2, starboard. This work is difficult and slow due to poor access and the recessing of bolt heads in the casting. (2) In view of the time that would be required and since all material from the gun chamber and pit has been recovered, except the deck lug castings, which it is understood are not desired by BuOrd [Bureau of Ordnance], salvage work on turret #2 and thus on the ship as a whole will be stopped as of this date.

CONCLUSIONS

This chapter is incomplete; there is much more work needed regarding two critical elements: modeling overall ship damage including the forward magazine explosion and its impact on the hull and archival research to locate divers' and engineers' sketches and drawings and additional documentation to incorporate into the FEM. Originally, we intended to contract this research out during the course of research between 1999–2007. Unfortunately, funding was inadequate to complete these tasks.

However, review of salvage records as reported in this chapter was sufficient to aid in selection of which portion of the hull to focus corrosion analysis upon and determine which portion of the ship should be modeled for the FEM. Understanding the extent of interior damage at the aft end of the explosion and where the fires occurred informed the selection of frames 70–90 for the FEM. Early damage reports indicated that the ship was intact aft of the area of frame 70 to 76, although fires had reached to frame 88 (Homann 1941a:1), and the main deck in that area was reported "buckled and twisted as are all bulkheads and partitions" (McClung n.d.) and sloping toward the bow (Paine 1943). These reports contradict somewhat *Arizona*'s first Acting Commander Geiselman's early report of December 17, 1941 where he states that the attack had "…completely destroyed the ship forward of frame 88 by fire and explosion of forward magazines. The fires being finally extinguished after burning two days. It is believed that considerable equipment aft of frame 90 can eventually be salvaged." There were no structural alterations other than removal of superstructure, turrets and crane aft of frame 66. Frame 70 would be the furthest forward the hull would remain sound, although the upper deck area forward of the galley has begun to sag (see Chapter 9).

The reason for selecting frames 70–90 for the focus of research is that corrosion measurements based on hull structure that had been subjected to blast and fire (the forward portion of Frames 70–90) would provide a conservative estimate for the aft hull portions and for the hull areas containing oil bunkers that were not subjected to either flames nor blast. Indications are that mild steel subjected to heat from fire and explosion may corrode underwater at a faster rate than mild steel that has not been heat damaged (see Chapter 5). Corrosion measurements for the forward portion of the modeled hull, if based upon heat-damaged steels in the frame 70–90 area, would most likely be higher than on areas aft of frame 90. Consequently, using corrosion rates based on damaged mild steel for the FEM would be conservative, that is, the model would incorporate the fastest corrosion rates likely to be encountered anywhere on the aft portion of the hull or within the interior. Prediction of structural change and eventual collapse would be conservative in that the projection would indicate the closest date for expected structural change.

REFERENCES

Bartholomew, C.A. Capt.
1990 *Mud, Muscle, and Miracles: Marine Salvage in the United States Navy*. Department of the Navy, Washington, D.C.

Commander Battle Force, US Pacific Fleet
January 29, 1942 Memorandum for File: Damages Sustained by the Ships of the Battle Force, Pacific Fleet as a result of the Japanese Air Raid on December 7, 1941. Wallin Papers, Box 2, 50 Salvage Reports, Naval History Center, Washington, D.C.

Commander Base Force to Commander in Chief, Pacific Fleet
December 28, 1941 Damaged Ships – Preliminary Estimates of Problems of Salvage. 7pp. Wallin Papers, Box 1,50 Salvage Reports, Naval History Center, Washington, D.C.

Davison, H.D.
1941 Statement of Ensign H. D. Davison, US Navy, USS *Arizona*. Wallin Papers, Box 2, 50 Salvage Reports, Naval History Center, Washington, D.C.

Flannigan, G. S. Ensign
1941 Statement of G.S. Flannigan, Ensign, D-V (a), USS *Arizona*. Wallin Papers, Box 2, 50 Salvage Reports, Naval History Center, Washington, D.C.

Fuqua, S.G. CDR
December 15, 1941 USS *Arizona* BB-39, Pearl Harbor Attack: Report of Salvage Operations Following Preliminary Dives to Inspect Hull Damage and to Determine what Sections of the Vessel Could be Entered. Memo From Commanding Officer, USS *Arizona* to Commander Battleships, Battle Force. Wallin Papers, Box 2, 50 Salvage Reports, Naval History Center, Washington, D.C.

1941 Statement, USN of the attack on the USS Arizona, 7 December 1941. Wallin Papers, Box 2, 50 Salvage Reports, Naval History Center, Washington, D.C.

Furlong, W.R.
March 15, 1942 Salvage operations on USS *Arizona*, USS *Oklahoma*, and USS *Utah* – Decision as to Extent of. Wallin Papers, Box 1,50 Salvage Reports, Naval History Center, Washington, D.C.

July 24, 1942 Memo from Commandant, Navy Yard, Pearl Harbor to the Vice Chief of Naval Operations. On file, USS *Arizona* Memorial Archives, Honolulu.

Geiselman, E.H.
December 17 1941 From Commanding Officer, USS Arizona to Commander Battleships, Battle Force. Material Damages sustained in attack on December 7, 1941. 3 pp. Wallin Papers, Box 2, 50 Salvage Reports, Naval History Center, Washington, D.C.

Haynes, H.E. Lt. CDR
November 14, 1943 Memo from Diving Supervisor to Salvage Superintendent re; Diving Operations in Connection with the Salvage of the USS *Arizona*. On file, USS *Arizona* Memorial Archives, Honolulu.

Homann, A. J. Cmdr.
January 28, 1942 (a) Material Damage Sustained in Attack on December 7. 1941. Memo from USS *Arizona* Commanding Officer to the Chief, Bureau of Ships. Wallin Papers, Box 2, 50 Salvage Reports, Naval History Center, Washington, D.C.

1942 (b) Information on Damage Control, ref. Pacific Fleet Conf. Lrt. No2Cl-42 of January 6, 1942. Memo from USS Arizona Commanding Officer to Chief, Naval Operations. Wallin Papers, Box 2, 50 Salvage Reports, Naval History Center, Washington, D.C.

Lott, A.S. General Editor
1978 *USS* Arizona *Ship's Data: A Photographic History*. Fleet Reserve Association, Honolulu.

Madsen, D.
2003 *Resurrection: Salvaging the Battle Fleet at Pearl Harbor*. Naval Institute Press, Annapolis.

McClung, M. L. Lt.
n.d. Survey of Damage on U.S.S. *Arizona*. Reference; Verbal Orders to Conduct a Survey of the Hull of U. S. S. *Arizona*. Correspondence from the Assistant Salvage Engineer to The Salvage Engineer. Wallin Papers, Box 2, 50 Salvage Reports, Naval History Center, Washington, D.C.

Miller J. D.
1941 Bombing of USS *Arizona*, Report of Ensign Jim D. Miller. Wallin Papers, Box 2, 50 Salvage Reports, Naval History Center, Washington, D.C.

National Research Council of the National Academies
2003 *Oil in the Sea III: Inputs, Fates, and Effects.* The National Academies Press, Washington, D.C.

Navy Department, Bureau of Construction and Repair
1913 *Detail Specifications for Building Battleship No. 39 for the United States Navy*. Government Printing Office, Washington D.C. On file, USS *Arizona* Memorial Archives, Honolulu.

Paine R.W.
October 7, 1943 Memo from Commandant Navy Yard , Pearl Harbor to Chief, Bureau of Ships. Subject: U.S.S. *Arizona* (BB-39) War Damage Report. On file, USS *Arizona* Memorial Archives, Honolulu.

Parker W.W.
1941 Statement of William W. Parker, SEA1c, USN. Wallin Papers, Box 2, 50 Salvage Reports, Naval History Center, Washington, D.C.

Raymer, Commander E. C.
1996 *Descent into Darkness Pearl Harbor, 1941: A Navy Diver's Memoir*. Presidio Press, Novato.

Salvage Diary, Pearl Harbor
1943 1 March – 1942 through 15 November, 1943. Industrial Department War Diary Collection, Naval Historical Center, Washington D.C.

Stillwell, Paul
1991 *Battleship* Arizona: *An Illustrated History*. Naval Institute Press, Annapolis.

Summary of Damage Reported to the Planning Section,
December 7, 1941.Wallin Papers, Naval Historical Center, Washington, D.C. Wallin Papers, Box 1,50 Salvage Reports, Naval History Center, Washington, D.C.

United States Pacific Fleet Battle Force,
n.d. USS *California*, Flagship, Memorandum No.7. Wallin Papers, Box 1, 50 Salvage Reports, Naval History Center, Washington, D.C.

Wallin, H.N. Cmdr.
December 7, 1941 Memorandum Covering Apparent Damage to Vessels in Pearl As of 1345 This Date. US Pacific Fleet, USS Pennsylvania, flagship. Wallin Papers, Box 1, 50 Salvage Reports, Naval History Center, Washington, D.C.

January 25, 1942 Progress of Salvage Work in Pearl Harbor. Wallin Papers, Box 1, 50 Salvage Reports, Naval History Center, Washington, D.C.

February 8, 1942 Present Situation with Respect to Salvage of Vessels in Pearl Harbor. 3pp. Wallin Papers, Box 1,50 Salvage Reports, Naval History Center, Washington, D.C.

1946 Rejuvenation of Pearl Harbor. Typescript sent to Admiral Nimitz and Navy Director of Public Information. Wallin Papers, Box 1,50 Salvage Reports, Naval History Center, Washington, D.C.

1968 *Pearl Harbor: Why, How, Fleet Salvage and Final Appraisal.* Naval History Division, Washington, D.C.

CHAPTER 4

Dynamics of the Physical Environment on USS *Arizona*

Curt D. Storlazzi, M. Katherine Presto, Michael E. Field, and Matthew A. Russell

INTRODUCTION

A variety of factors have been identified that directly influence metal corrosion on shipwrecks, including water composition (dissolved oxygen, pH, salinity and conductivity), temperature and extent of water movement (North and MacLeod 1987:68).

Oxygen reduction is typically the main cathodic reaction occurring in steel exposed to seawater, so dissolved oxygen availability at the cathodic site controls the corrosion rate, with higher dissolved oxygen content resulting in higher corrosion. Water at the ocean's surface is generally oxygen-saturated, so overall dissolved oxygen content depends on the amount of mixing that occurs with surface water—increased water movement and mixing results in elevated dissolved oxygen levels. In addition, temperature and dissolved oxygen are inversely proportional, so lower temperature results in increased dissolved oxygen. The pH level is indicative of overall corrosion activity. In normal seawater, pH ranges from 7.5 to 8.2, but levels below 6.5 are found under concretion covering actively corroding metal. Lower pH levels (more acidic) typically characterize active or increased corrosion levels. Salinity is closely related to the corrosion rate of steel in water, so increased salinity usually results in higher corrosion rates. This is evident when comparing metal preservation in freshwater compared to seawater environments—freshwater lakes typically exhibit better preservation of iron and steel. There are several ways that higher salinity affects corrosion, including increasing conductivity (which facilitates movement of ion between anodic and cathodic areas), increasing dissolved oxygen and supplying ions that can catalyze corrosion reactions, among others (North and MacLeod 1987:74). Higher conductivity can increase corrosion by increasing the movement of ions during the corrosion process.

In general, corrosion increases as temperature increases. Under controlled laboratory conditions, corrosion rate doubles for every 10°C rise in temperature. This relationship is complicated, however, by the effect of temperature on both dissolved oxygen and biological growth. Warmer water supports increased marine growth, which contributes to concretion formation on steel in seawater and that, in turn, generally reduces corrosion rates. In addition, as discussed above, lower temperature results in higher dissolved oxygen content, which consequently means increased corrosion (North and MacLeod 1987:74).

Water movement from waves and currents on a site affects corrosion in several ways, but generally high-energy environmental conditions results in higher corrosion rates. Active water movement can contribute to mechanical erosion of metal surfaces and can also impede development of protective concretion layers by removing accumulating ions before they can precipitate and begin the concretion formation process. Waves and currents also contribute to water mixing and aeration that result in increased dissolved oxygen levels (North and MacLeod 1987:74).

Factors that affect corrosion on metal shipwrecks are complicated and interrelated. Reducing one key factor can increase another, and the results are often unpredictable. It is clear, however, that in order to understand the corrosion history of an object, even a complex object like a World War II battleship, and to begin to define the nature and rate of deterioration affecting the object, an understanding of the various environmental factors at play is necessary. An important aspect of the USS *Arizona* Preservation Project was long-term monitoring of oceanographic and environmental parameters on the site. This was accomplished with *in situ* multiparameter instruments placed on the hull and on the seabed to the side of the vessel. Interior conditions were also measured using ROV-deployed instruments.

EXTERIOR DATA COLLECTION

LONG-TERM *IN SITU* MONITORING, 2002-2005

U.S. Geological Survey (USGS) and National Park Service (NPS) personnel collected long-term, high-resolution physical and chemical oceanographic measurements at the USS *Arizona* Memorial (USAR) in 2002–2005 to better understand the nature of the environment surrounding the mostly submerged historic ship, and to determine long-term, seasonal variability in key parameters that affect corrosion. Scientists used a number of bottom-mounted, multi-parameter instruments deployed in water depths less than 10 m to collect survey and time series environmental data.

Researchers calibrated and deployed a SonTek Triton Acoustic Doppler Velocimeter (ADV) wave-height and current meter and a YSI 6600 Multiparameter Sonde on *Arizona* in November 2002. These instruments have internal memory and batteries and can be left *in situ* for up to 60 days, recording data multiple times an hour. The instruments were retrieved and downloaded, then recalibrated and deployed every 60 days by USAR staff. The data were sent to the SRC in Santa Fe, New Mexico, and the USGS in Santa Cruz, California, for compilation and analysis. The instruments collected baseline data including wave height and direction and current velocity and direction around the vessel, and basic environmental parameters including pH, temperature, salinity, dissolved oxygen, oxygen reduction potential and conductivity. The purpose of these measurements was to collect hydrographic data to better constrain the nature of the physical and chemical environment on the submerged vessel hull and near the Memorial to determine temporal and spatial variability. Two RD Instruments 600 kHz Acoustic Doppler Current profilers (ADCP) were later deployed for a one-month period in April–May 2005 in the same locations as the SonTek instrument for additional data collection.

Project Objectives

The objective of the instrument deployments was to understand how waves, currents and water column properties such as water temperature, salinity, pH, turbidity, oxygen reduction potential and dissolved oxygen in the vicinity of the Memorial vary spatially and temporally.

These data were collected to support the NPS-SRC research to understand and characterize the nature and rate of natural processes affecting deterioration of USS *Arizona*. To meet these objectives, flow and water column properties close to *Arizona*'s hull were investigated. The first two instrument packages were deployed over a period spanning 14 months to investigate variability over daily-to-seasonal time scales. The objective of the third instrument deployments was to understand how currents and temperature in the vicinity of the Memorial vary over two spring-neap tidal cycles. These data supplemented the single-point measurements made between 2002–2004.

Study Area

The instrument deployments were conducted adjacent to and on USS *Arizona*'s hull (Figure 4.1). The SonTek ADV was deployed in 10 m of water roughly 25 m southeast of *Arizona*'s port beam below the Number 1 turret from November 2002, through November 2003. In November 2003, the ADV was re-deployed in 10 m of water roughly 25 m northwest of USS *Arizona*'s starboard beam below the Number 1 turret and logged data at that location until January 2004. The seafloor at both of these sites is an organic-rich, very well sorted fine silt/mud. The YSI Sonde was deployed amidships on *Arizona*'s main deck just forward of the Number 3 barbette and just aft of the Memorial from January 2003 through January 2004. Vertical profiles of the water column using the Sonde were made off the USS *Arizona* Memorial's dock in February 2003. Two ADCPs were deployed concurrently at the two ADV sites to either side of the Number 1 turret from April 2005 through May 2005. All diving, mobilization and demobilization were based from the USS *Arizona* dock.

Operations

This section provides information about personnel, equipment and vessels used during equipment deployments. See Tables 4.1 and 4.2 for personnel involved in this experiment and Tables 4.3 and 4.4 for complete deployment information for the instruments.

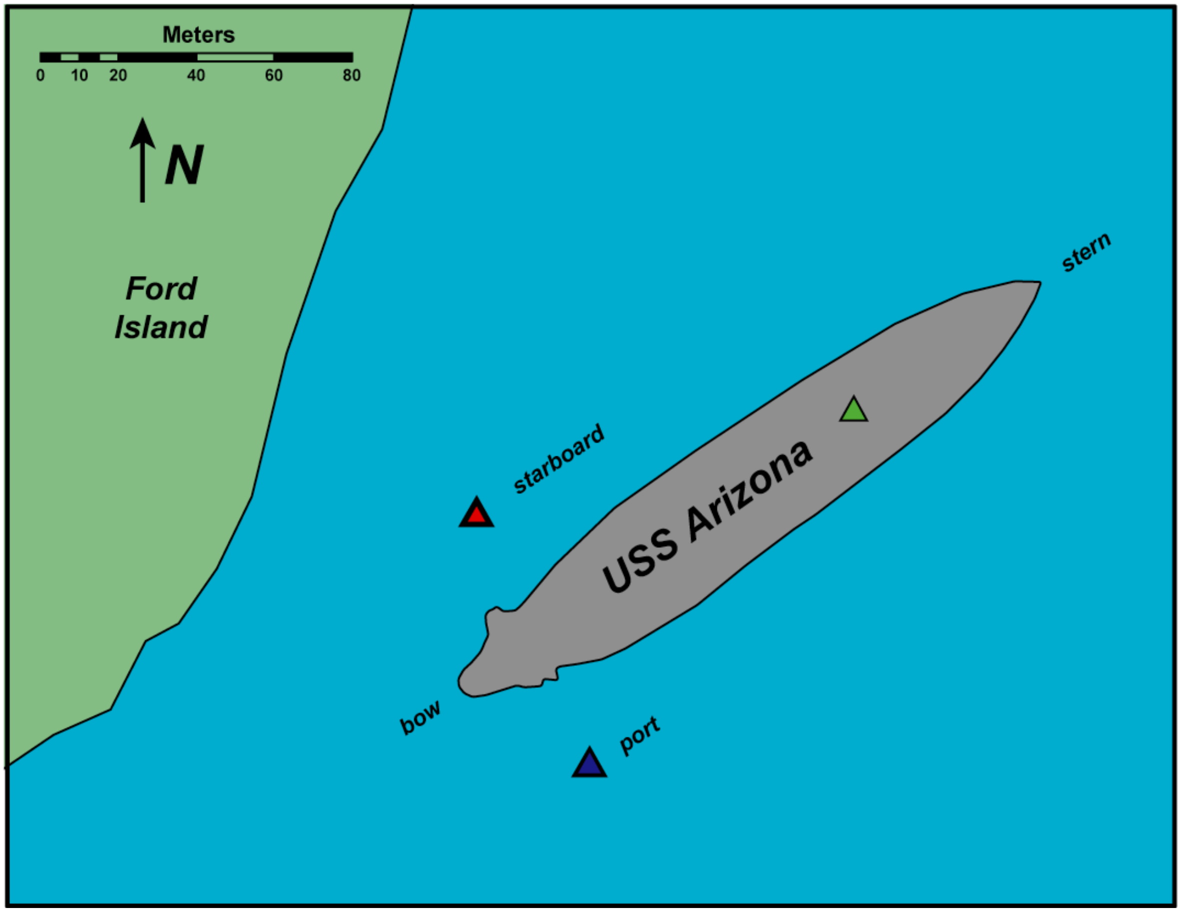

Figure 4.1. Map showing the spatial distribution of instrument packages in the study area relative to the USS *Arizona*'s hull and Ford Island.

Person	Affiliation	Responsibilities
Curt Storlazzi	USGS	Chief scientist, scuba diver
Matthew Russell	NPS-SRC	Co-chief scientist, led scuba diving operations
Marshall Owens	NPS-USAR	USAR Memorial curator, led refurbishment operations
Michael Field	USGS	Scientist, scuba diver
Larry Murphy	NPS-SRC	Scientist, scuba diver
Michael Freeman	NPS-USAR	Scuba diver

Table 4.1. Personnel involved in long-term instrument deployments, 2002–2004.

Person	Affiliation	Responsibilities
Curt Storlazzi	USGS	Chief scientist, scuba diver
Matthew Russell	NPS-SRC	Co-chief scientist, led scuba diving operations
Kathy Presto	USGS	Scientist, lead instrument technician
Jennifer Burbank	NPS-USAR	USAR Memorial ranger, diver, led recovery operations
Joshua Logan	USGS	Scientist, scuba diver, GIS Technician
Thomas Reiss	USGS	Scientist, dive safety officer

Table 4.2. Personnel involved in instrument deployment, 2005.

Instrument	Depth (m)	Date Deployed	Date Recovered	Latitude (dd)	Longitude (dd)
SonTek Triton	10	11/21/2002	1/30/2003	21.36415	-157.95054
SonTek Triton	10	1/30/2003	3/7/2003	21.36415	-157.95054
YSI 6600 Sonde	3	1/30/2003	3/7/2003	21.36494	-157.94986
SonTek Triton	10	3/21/2003	5/7/2003	21.36415	-157.95054
YSI 6600 Sonde	3	3/21/2003	5/7/2003	21.36494	-157.94986
SonTek Triton	10	5/15/2003	7/2/2003	21.36415	-157.95054
SonTek Triton	10	7/8/2003	8/29/2003	21.36415	-157.95054
SonTek Triton	10	8/29/2003	10/10/2003	21.36415	-157.95054
YSI 6600 Sonde	3	8/29/2003	10/10/2003	21.36494	-157.94986
SonTek Triton	10	10/23/2003	11/5/2003	21.36415	-157.95054
YSI 6600 Sonde	3	10/24/2003	11/20/2003	21.36494	-157.94986
SonTek Triton	10	11/20/2003	1/13/2004	21.36415	-157.95054
YSI 6600 Sonde	3	11/20/2003	1/22/2004	21.36494	-157.94986

Table 4.3. Instrument package deployment log, 11/2002–1/2004.

Instrument	Depth (m)	Date Deployed	Date Recovered	Latitude (dd)	Longitude (dd)
Starboard	9	4/2/2005	5/1/2005	21.364684	-157.950756
Port	10	4/2/2005	5/1/2005	21.364206	-157.95055

Table 4.4. ADCP deployment log, 4/2005–5/2005

Equipment and Data Review

Three primary instruments acquired data during the deployments. The first instrument was a SonTek Triton wave/tide gauge (Figure 4.2a). The primary sensor on this package is an upward-looking 10 MHz Acoustic Doppler Velocimeter (ADV), which collects three-dimensional single-point measurements of current velocity and acoustic backscatter data. A pressure sensor on the Triton provided tide data and spectral wave information. The Triton employed two different sampling schemes: First, it sampled the mean currents by averaging the current speeds over a 1-min window every 10 min. Second, it sampled the surface wind waves by collecting current and water depth data over an 8.5-min window every 2 hours.

The second primary instrument employed was an YSI 6600 Multi-parameter Sonde (Figure 4.2b). The YSI Sonde collected single-point measurements on water temperature and salinity, pH, dissolved oxygen and oxygen-reduction potential when deployed on the hull 3 m below the surface; the YSI was also used in profiling mode, collecting vertical profiles of water temperature and salinity, pH, dissolved oxygen and oxygen-reduction potential. When used in profiling mode, the YSI was lowered from the surface to the seafloor in the early morning and

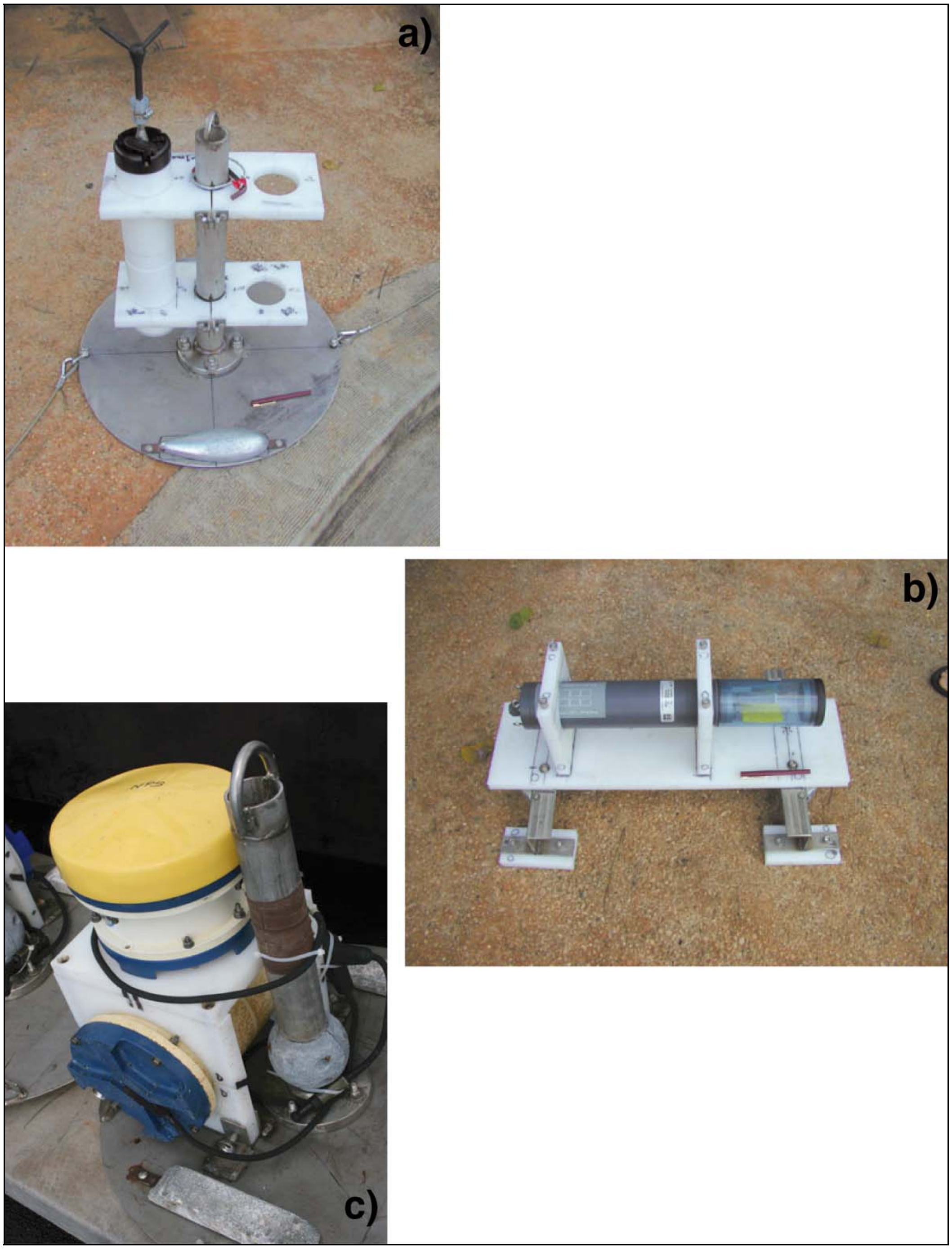

Figure 4.2. Photographs of instrument packages and their mounts. a) The Sontek Triton ADV and sea bed mount. This mount was designed to be able to simultaneously deploy the YSI 6600 Sonde in the empty bracket on the right side of the photograph; note the pen for scale. b) The YSI 6600 Sonde and hull mount; note the pen for scale. c) RD Instruments ADCP and its sea bed mount. The ADCP transducers and the pressure and temperature sensors are under the yellow protective cap (~20 cm diameter for scale).

the late afternoon for three consecutive days. During these profiles all the sensors on the YSI sampled at once per second.

The third primary instrument used to acquire data during the deployments were two RD Instruments 600 kHz Acoustic Doppler Current profilers (ADCP) (Figure 4.2c). These collected three-dimensional vertical profile measurements of current speed and direction in 0.5 m bins (sampling volumes) every 0.5 m from 1.0 m above the seafloor up to the water surface and single-point measurements of water temperature 0.5 m above the seafloor; a pressure sensor on the ADCP measured water level data. The ADCP sampled mean currents, water level and water temperature by averaging over a 1-min window every 4 min.

The first two instrument packages were typically deployed for approximately one- to two month periods, as limited by the power consumption and sensor sampling rates, while the third was deployed for only a one-month period (see Tables 4.3 and 4.4). The instrument specifics and sampling schemes are listed in Appendix A for the SonTek Triton ADV, Appendix B for the YSI 6600 Sonde, and Appendix C for the RD Instruments ADCP (Storlazzi, et al. 2004; Storlazzi, et al. 2005). Daily data on meteorologic forcing over the study period were recorded at the Honolulu International Airport roughly 5 km southeast of the study site. These digital data were downloaded and compiled from the National Climate Data Center (2005).

Deployment/Recovery Operations

Prior to installation of the SonTek ADV in 2002, diving scientists established a secure guideline from *Arizona*'s hull out to the location where it would be deployed. The ADV and its semi-permanent mount were initially deployed by lowering it just below the water's surface where scuba divers attached a lift bag and detached the lifting line. The divers followed a marker line to the sea floor to move the instrument package into place. The divers secured the instrument package with cables attached to sand anchors embedded in the seafloor (Figure 4.3). The same procedure was followed for the later ADCP deployment in 2005. The YSI Sonde was placed in its semi-permanent mount by researchers who swam it out from the USAR dock for deployment in 2002. Periodic recovery and redeployment operations for the ADV and Sonde between 2002–2004 involved researchers removing the instruments from their mounts,

Figure 4.3. The SonTek ADV in place on the harbor bottom adjacent to USS *Arizona* (NPS Photo by Brett Seymour).

swimming them back to the dock for download and battery replacement; they were then redeployed (Figure 4.4). The vertical profiles collected with the YSI Sonde were done from the USAR dock. These entailed lowering the YSI Sonde to just below the surface for a minute to allow all of the sensors to equilibrate, then slowly lowering the YSI Sonde from the surface, down to the sea floor, then bringing it slowly back up to the surface.

Data Acquisition and Quality

SonTek Triton ADV data were acquired on 362 days during the 14-month period between November 2002 and January 2004, for more than 85% data coverage over the entire experiment period. Instrument refurbishment and battery failure accounted for the 64 days during these 14 months when no data were recorded. The ADV produced almost 77,750 observations from each sensor. Data quality was generally very high. Scientists archived the raw Triton data, and copies of the data were post-processed to remove spurious data whenever the beam correlation dropped below 70%. The post-processed data were saved and copies were

Figure 4.4. USS Arizona Memorial diver retrieving YSI Sonde (NPS Photo by Brett Seymour).

de-sampled to hourly intervals to better visualize longer-term variability; these desampled copies of the data were also saved and archived (Storlazzi, et al. 2004).

The YSI Sonde produced data on 59% of days deployed (215 out of 362 days), which resulted in just over 23,000 observations from each sensor. Data quality was generally good, exceptions were from improperly calibrated sensors or when fouled by biologic growth. The post-processed data were saved and copies were de-sampled to hourly intervals to better visualize longer-term variability; these de-sampled copies of the data were also saved and archived. Six vertical profiles were collected using the YSI 6600 Sonde, with 100% data recovery from the temperature, conductivity, and dissolved oxygen sensors. Due to sensor malfunction, no pH or oxygen-reduction potential data were recorded during any of the six profiles (Storlazzi, et al. 2004).

The RD Instruments ADCPs acquired current speed, current direction and near-bed water temperature data for 30 days between April 2 and May 1, 2005, yielding 100% coverage over the entire experiment period. Each ADCP made more than 10,400 observations of current speed, current velocity and acoustic backscatter from each of the 28 bins (>290,000 total samples per instrument) over the study period. Data quality was very high. The ADCP data near the surface displayed slightly lower correlation due to bubble interference with the transducers. This loss of data from the bins closest to the surface is common to most upward-looking ADCPs and was expected. The raw ADCP data were archived and copies of the data were post-processed to remove all "ghost" data from above the surface. All data collected when the beam correlation dropped below 70% were discarded for visualization and analysis. Post-processed data were saved and copies were desampled to hourly intervals to identify longer-term variability; these desampled copies of the data were also saved and archived (Storlazzi, et al. 2005).

Results

This section reviews data collected by all systems during deployments and addresses significance of the findings to characterizing local oceanographic conditions in the study area.

Meteorologic Forcing

The Hawaiian Islands, situated at roughly 21° North, are in the Trade wind belt. Consequently, the study area is dominated by very low wind variability during the summer periods when the Trade winds blow consistently; insolation (solar heating) and thus air temperatures are high and precipitation is low. During the winters, when extratropical lows and frontal systems propagate through the Hawaiian Islands causing precipitation, weaker and more variable winds, decreased insolation and, thus, lower air temperatures occur. Based on oceanographic measurements made at USAR, decreased air temperatures and precipitation typically reduce water temperature and salinity in Pearl Harbor. The Trade winds, which generally cause the highest sustained wind speeds (excluding tropical cyclones) during the spring, summer and fall, are topographically steered around the Koolau Range to the east of Pearl Harbor, often approaching the south shore of Oahu from the south or southeast and resulting in strong winds to the north or northwest over USAR. During the winter months, passage of fronts and extratropical lows to the north of the Hawaiian Islands results in strong northerly winds being funneled south between the Waianae Range to the west of Pearl Harbor and the Koolau range to the East, resulting in strong winds to the south over USAR. These winds can drive surface currents and cause mixing of the water column at USAR.

Waves

Waves in Pearl Harbor during the study were generally extremely small, with significant wave heights (*Hsig*) on the order of cm's, with a range of 0.01 m to 0.08 m and a mean *Hsig* ± one standard deviation of 0.03 ± 0.01 m. Dominant wave periods (*Td*) are in a very narrow range between 19.85 and 20.38 sec, with a mean *Td* ± one standard deviation of 20.19 ± 0.08 sec; these low height, long period waves all were observed to come out of the southern quadrant (160º-200º). This narrow band range and corresponding low wave heights suggest that the pressure sensor along the 10-m isobath is at or near its resolution limits relative to the incident wave frequency. Because the depth of penetration of wave-induced pressure fluctuations and orbital motions decreases exponentially with depth and is dependant on wave height and period, it appears that the SonTek ADV's pressure sensor is only able to resolve longer period motions at these small wave heights. Thus, the shorter period wind waves typically observed in the afternoon when the Trade winds are blowing 10-20 m/sec are too small in height and too short in period for the pressure sensor to resolve from its depth of 10 m. The 20-sec period waves that are resolvable by the pressure sensor are likely long period ground swell (North Pacific winter swell or South Pacific summer swell) that has enough energy to propagate up the entrance channel of Pearl Harbor and into the East Loch past USAR.

In addition to these natural small, long-period swells, the pressure sensor record was often overwhelmed by high-amplitude, short-period (2-8 sec) modulations. These modulations appear to be due to large vessels passing over or by the Sontek instrument package, for they are anomalously large and have southeasterly (90º-150º) or northwesterly (270º-330º) directions, likely the result of incident waves and waves reflected off *Arizona*'s hull, respectively.

Tides

Pearl Harbor tides are of the mixed, semi-diurnal type with two uneven high tides and two uneven low tides per day; thus the tides change just over every 6 hours. The mean daily tidal range during the study was roughly 0.6 m, while the minimum and maximum daily tidal ranges are 0.4 m and 0.9 m, respectively (Figure 4.5). The lunar tidal cycle drives the magnitude of the tidal currents, with the highest tidal current speeds occurring during the spring tides (new and

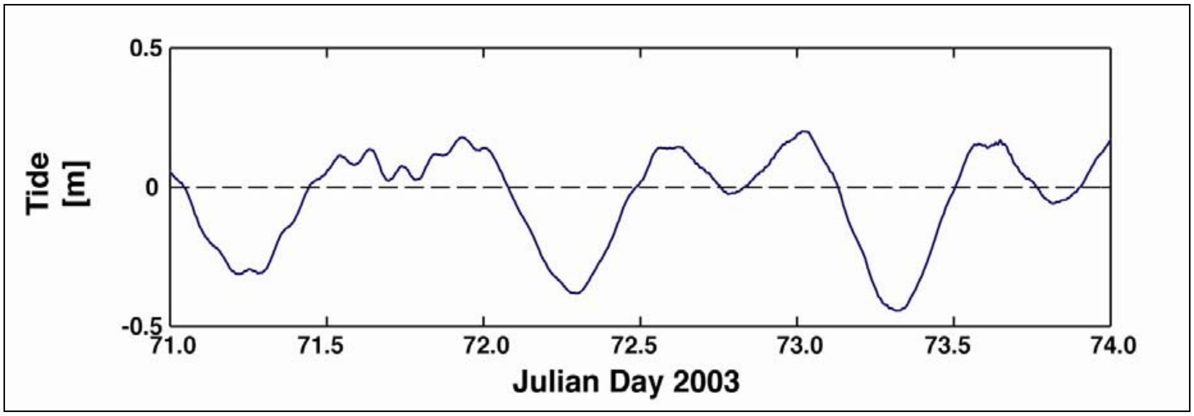

Figure 4.5. Typical tidal data from USS *Arizona*.

full moons) and the weakest during the neap tides (quarter moons). While tides control the majority of the variability in current speed and direction, insolation-driven trade wind intensification also appears to slightly influence daily variability. When the trade winds blow at high speed in the early to late afternoon, the net flow at the 10-m site appears to take on a more northwesterly component. This shift might be due to an upwelling-type of phenomena, oceanic water being drawn into the harbor to replace the surface water flushed offshore by the trade winds. We do not have information at this time that indicates which process or combination of processes is responsible for the observed intensification of northeasterly flow during the afternoon.

Currents

Most daily variability in current speed and direction at the study site is due to the semi-diurnal (12.4 hour) and diurnal (24.8 hour) tides. As the tide rises (floods), currents in Pearl Harbor flow to the north; conversely, as the tide falls (ebbs), the currents flow to the south. Mean current speeds ± one standard deviation approximately 1 m below the water surface are 0.028 ± 0.019 m/s off the starboard (northwestern) side of the hull and 0.023 ± 0.013 m/s off the port (southeastern) side of the hull. Close to the bottom, mean current speeds ± one standard deviation 1 m above the seafloor are 0.010 ± 0.007 m/s off the starboard (northwestern) side of the hull and 0.027 ± 0.015 m/s off the port (southeastern) side of the hull. Of note are the slightly different orientations in both instantaneous and net flow to the port and starboard sides of the USS *Arizona*'s hull. Off the starboard side, the flow is predominantly oriented north-

northeast or south-southwest, roughly parallel Ford Island's shoreline in the vicinity of the USS *Arizona*. Off the port side, however, the flow is predominantly oriented east-northeast or west-southwest, roughly parallel to the main trend of the East Loch of Pearl Harbor. These differences in orientation imply steering, not only by the bathymetry, but also by the USS *Arizona*'s hull (Figure 4.6).

Net flow at the surface along both sides of the USS *Arizona*'s hull was to the southeast at roughly 0.02 m/s. Assuming near-surface flow remained constant through this section of Pearl Harbor, the mean current speed of 0.02 m/s would result in a total replacement of water along the 185-m length of the hull in just over 2.6 hours. Net flow 1 m below the surface and 1 m above the seafloor along both sides of the USS *Arizona*'s hull were to the northwest at approximately 0.02 m/s and 0.01 m/s, respectively. Assuming near-bed flow remained constant through this section of Pearl Harbor, these mean current speeds would result in a total replacement of water along the 185-m length of the hull in just over 2.6 hours and 5.2 hours, respectively. However, because oscillatory tidal flows enhance these mean flow speeds, the actual replenishment time would typically be shorter.

The differences in current speed, both vertically and from one side of the hull to the other, result in velocity shear, which, in turn, likely increases turbulence and mixing. The values of vertical shear varied from 0.025 ± 0.015 1/s off the starboard (northwestern) side of the hull and 0.038 ± 0.023 1/s off the port (southeastern) side of the hull. The shear was generally highest during the falling tides. The vertical velocity shear, by moving seawater of a given density, would impart a vertical variation in current-induced force on the hull. Seeing that seawater in Pearl Harbor has a density around 1023 kg/m^3 (temperature~25 °C and a salinity~33 Practical Salinity Units, PSU, or parts per thousand), the mean current-induced force on the starboard (northwestern) side of the hull is 0.175 ± 0.131 N/m^2 and 0.291 ± 0.259 N/m^2 on the port (southeastern) side of the hull (Figure 4.7).

<u>Water Column Properties</u>

The water column properties collected include variations in acoustic backscatter (dB), temperature (ºC), salinity (PSU), pH, oxygen-reduction potential (mV), and dissolved oxygen (%). Their ranges, variability and potential causes for their variability are discussed here.

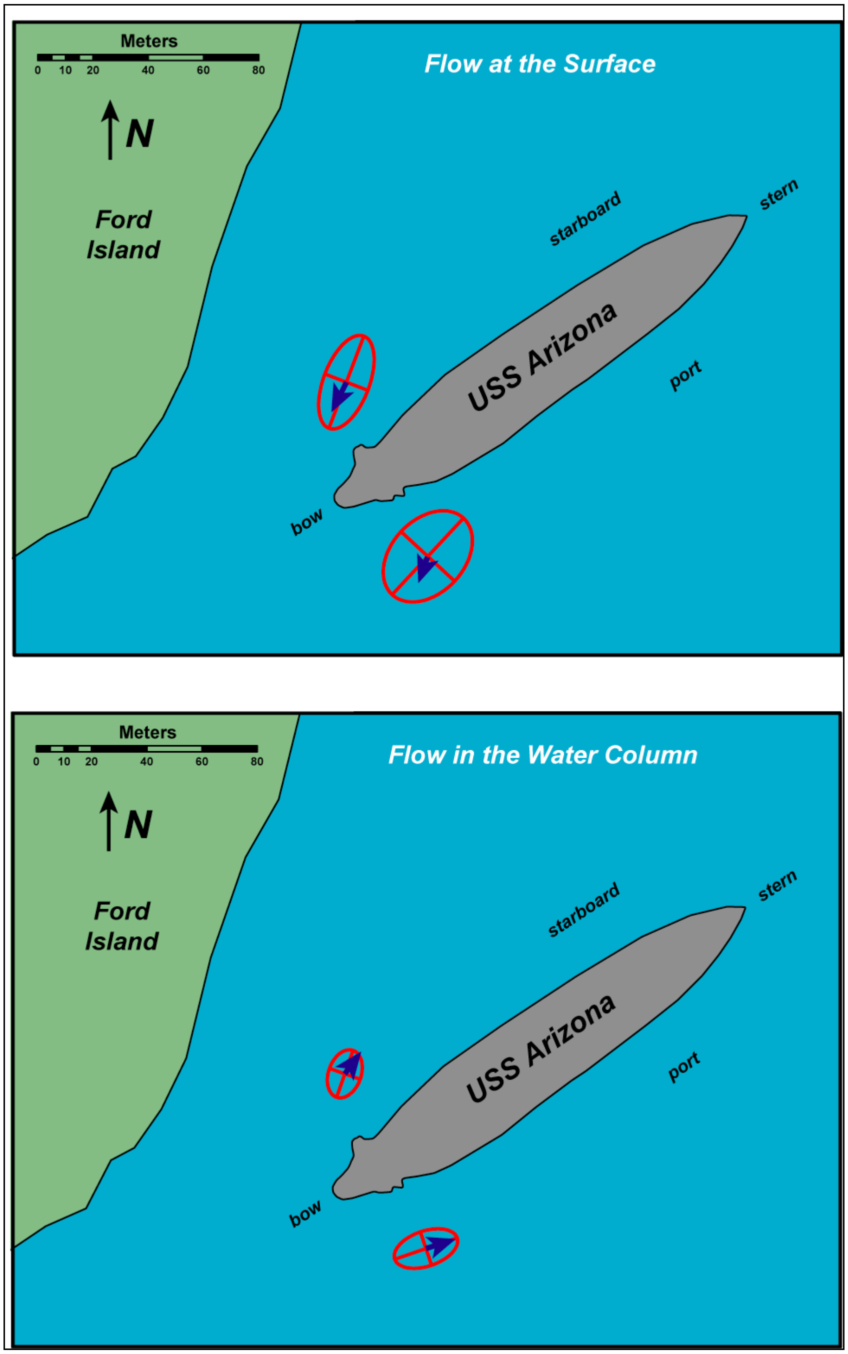

Figure 4.6. The orientation of mean flow and its variability in the water column adjacent to the *Arizona*. TOP: Flow at the surface. BOTTOM: Flow in the water column. The red ellipses denote the magnitude of major and minor axes of variability in flow; the blue vectors denote the magnitude and direction of mean flow. Note that surface flow is stronger and oriented to the southwest while flow within the water column is weaker and is oriented to the northeast. Off the starboard side, the flow is predominantly oriented north-northeast or south-southwest, roughly parallel Ford Island's shoreline; off the port side, however, the flow is predominantly oriented east northeast or west-southwest, roughly parallel to the main trend of the East Loch of Pearl Harbor.

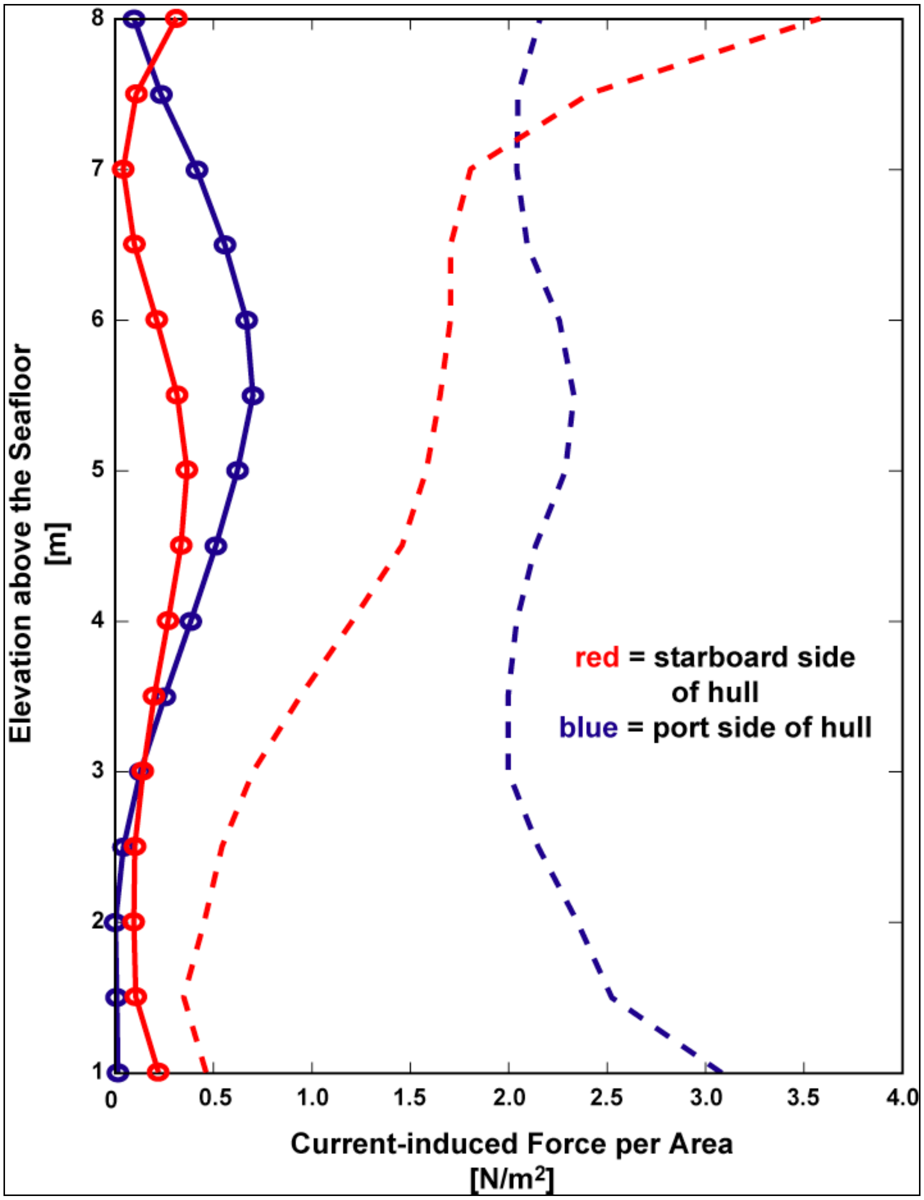

Figure 4.7. Vertical profiles of the current-induced force on the USS *Arizona*'s hull. Dashed lines are ± 1 standard deviation. Note that the force generally is at a maximum 6 m above the seafloor (4 m below the surface).

Acoustic Backscatter

Over the period of study, the acoustic backscatter, which is a function of the particulate matter in the water column, 0.6 m above the seabed at the site along the 10-m isobath ranged between 145.48 dB and 281.52 dB, with a mean backscatter ± one standard deviation of 179.86 ± 20.64 dB. In general, highest acoustic backscatter measurements occurred during winter months and the lowest during the summer months. This peak in acoustic backscatter suggests that wintertime phenomena causes increased particulate matter concentrations in the area around USS *Arizona*. Potential reasons for this increase in backscatter include: precipitation and runoff in other regions of Pearl Harbor that would introduce fine-grained particulate matter into the harbor that is advected into the area around *Arizona*, or nutrients introduced into Pearl Harbor from runoff might cause algal blooms that increase acoustic backscatter.

Acoustic backscatter was generally higher when the flow was to the south, likely caused by fine particulate matter being drawn down from the shallow regions of the northern half of the harbor. Acoustic backscatter also appeared to slightly increase during the early to mid-afternoon and decrease through the night (Figure 4.8); this suggests that either: (a) daily insolation-induced Trade wind intensification during the day creates larger Trade wind-driven waves that suspend more fine-grained sediment that is then advected by the sensor, or (b) more vessel traffic and prop wash during the day in the harbor tends to suspend more of the fine-grained bed sediment, which settles during the evening and night when vessel traffic subsides. We do not have information at this time that indicates which process or combination of processes is responsible for the observed intensification of acoustic backscatter during either the wintertime or in the afternoons and evenings.

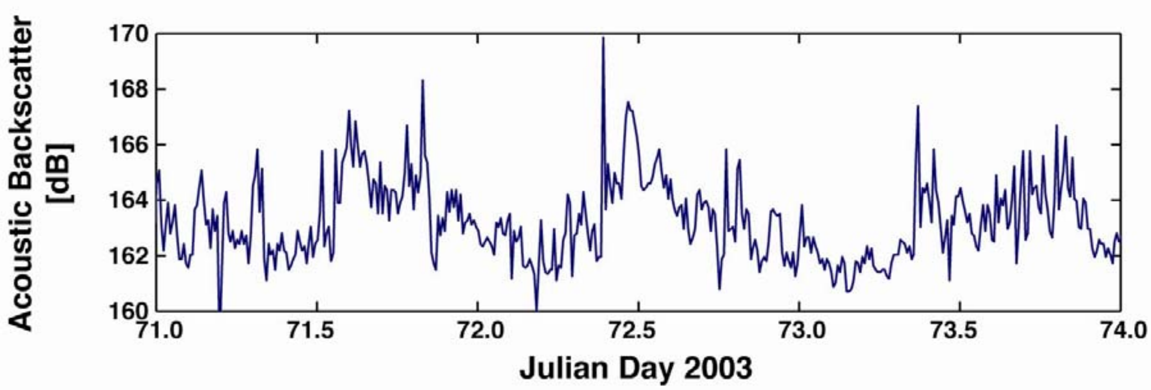

Figure 4.8. Typical acoustic backscatter data from USS *Arizona*.

Temperature

Over the period of study, water temperatures at the site along the 10-m isobath ranged between 23.14 °C and 27.52 °C, with a mean temperature ± one standard deviation of 26.03 ± 1.17 °C. The water temperature atop USS *Arizona*'s hull along the 3-m isobath ranged between 29.42 °C and 19.15 °C, with a mean temperature ± one standard deviation of 24.55 ± 2.08 °C. At both sites, insolation typically warmed the water, often more than 0.7 °C atop USS *Arizona*'s hull, but only 0.1-0.3 °C along the 10-m isobath. Thermal stratification, measured as the temperature difference between the sensor on the hull (depth~3 m) and the temperature sensor along the 10-m isobath, ranged between 0 and 2.5 °C, which reflects a distinct thermocline in the harbor's waters (Figure 4.9). This general trend of warmer water overlying cooler near-bed water causes the water column to be thermally stratified and stable, reducing interaction of the near-bed waters with the surface waters due to density contrasts.

Along the 10-m isobath, the variability in water temperature was greater off the starboard (northwestern) side of the hull between the USS *Arizona's* hull and Ford Island. In general, the near-bed water off the starboard (northwestern) side of the hull was slightly (0.02 ± 0.10 °C) warmer that off the port (southeastern) side of the hull (Figure 4.10). The greater stability off the port (southeastern) side of the USS *Arizona*'s hull is likely caused by greater mixing due to currents, which act to minimize temperature fluctuations caused by insolation or submarine groundwater discharge. We do not have information at this time that indicates that these processes are the cause of the temperature differences between the two sites.

Salinity

Over the period of study, the salinity at the site along the 3-m isobath ranged between 16.78 PSU and 42.56 PSU, with a mean salinity ± one standard deviation of 34.33 ± 4.25 PSU. Salinity tended to correlate positively with water temperature. This correlation is clearly seen when probable large surface runoff or groundwater effluences are advected by the YSI Sonde during the winter months, causing the temperature and salinity to rapidly drop. Gradual increases back to prevent levels over the course of a few days, likely due to current-induced mixing, follow these sharp decreases.

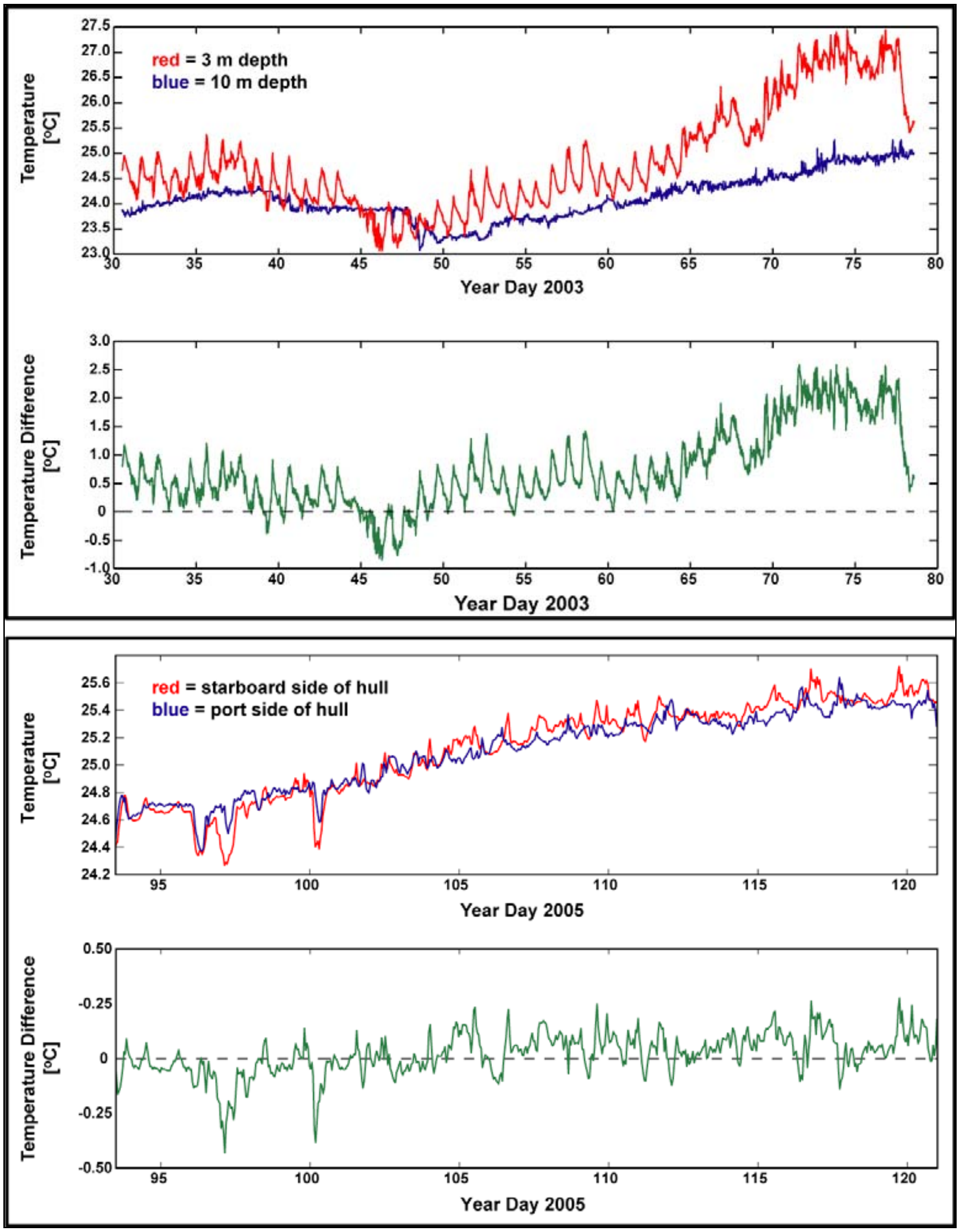

Figure 4.9. Differences in water temperature around the USS *Arizona*. TOP: Near-bed (10 m) and near-surface (3 m) temperatures and the resulting thermal stratification. BOTTOM: Concurrent water temperatures off the port and starboard sides of the hull and the resulting thermal gradient. While both the port and starboard temperatures both follow the same long-term trends, note the greater fluctuations in water temperature off the starboard side; this likely results from less mixing of the water column off the starboard side.

pH

Over the period of study, water pH at the site along the 3-m isobath ranged between 7.60 and 9.10, with a mean pH ± one standard deviation of 8.04 ± 0.15. Most variability in pH is at daily timescales; pH tends on average to rapidly increase from approximately 7.9 at roughly 09:00 each morning to more than 8.1 around 13:00, then decrease down to nominal levels of 7.9 by 21:00 (Figures 4.10 and 4.11). This daily increase, which is often on the order of 0.05 to 0.35, suggests that pH levels at the study site are related to daily insolation-driven warming or insolation-driven Trade wind intensification and Trade-wind wave-induced mixing.

Oxygen-Reduction Potential

Over the period of study, the oxygen-reduction potential at the site along the 3-m isobath ranged between 150.0 mV and 397.2 mV, with a mean oxygen-reduction potential ± one standard deviation of 289.2 ± 50.6 mV. Oxygen-reduction potential had an *inverse* relationship with pH and the percentage of dissolved oxygen during the summer months, with oxygen-reduction potential decreasing during the daytime and increasing into the night, attaining it greatest values just before sunrise. However, during the winter months when temperature and salinity were more variable, oxygen-reduction potential had more variable *positive* relationship with pH and the percentage of dissolved oxygen, suggesting that changes in salinity due to precipitation and/or submarine groundwater discharge might be impacting the data (Figures 4.10 and 4.11).

Dissolved Oxygen

Over the period of study, the dissolved oxygen levels in the water at the site along the 3-m isobath ranged between 0% and 288.5%, with a mean dissolved oxygen level ± one standard deviation of 69.5 ± 58.8%. Similar to the pH levels, most variability in dissolved oxygen levels is at daily timescales; dissolved oxygen tends to rapidly increase at roughly 09:00 each morning, peak around 13:00, then decrease down to nominal levels by 21:00 (Figures 4.10 and 4.11). This daily increase of 5-20% suggests that dissolved oxygen levels at *Arizona* are related to daily

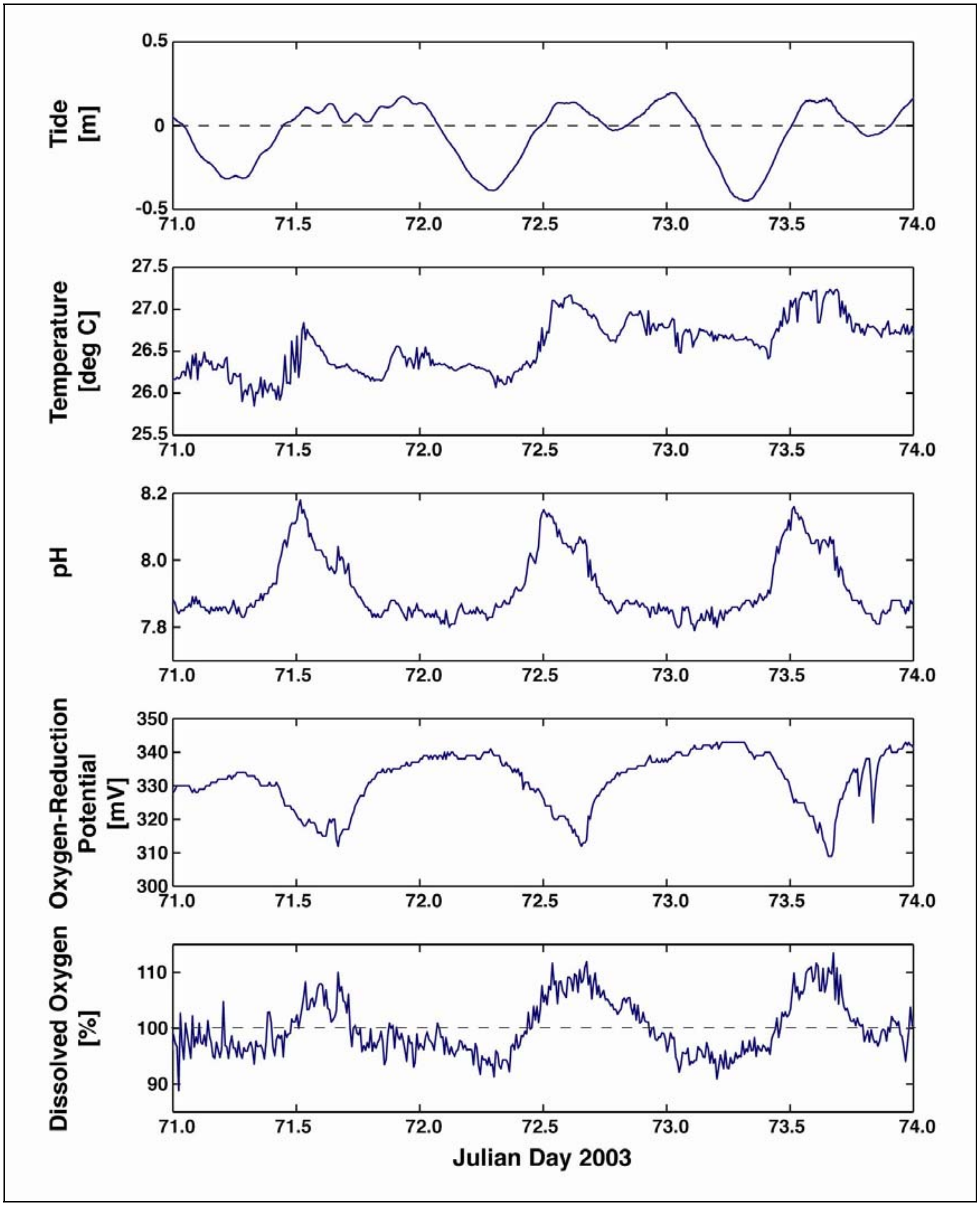

Figure 4.10. Graphic illustrating positive correlation between tide, temperature, ph, and dissolved oxygen; and an inverse correlation with oxygen reduction potential on the USS *Arizona* over a several day period.

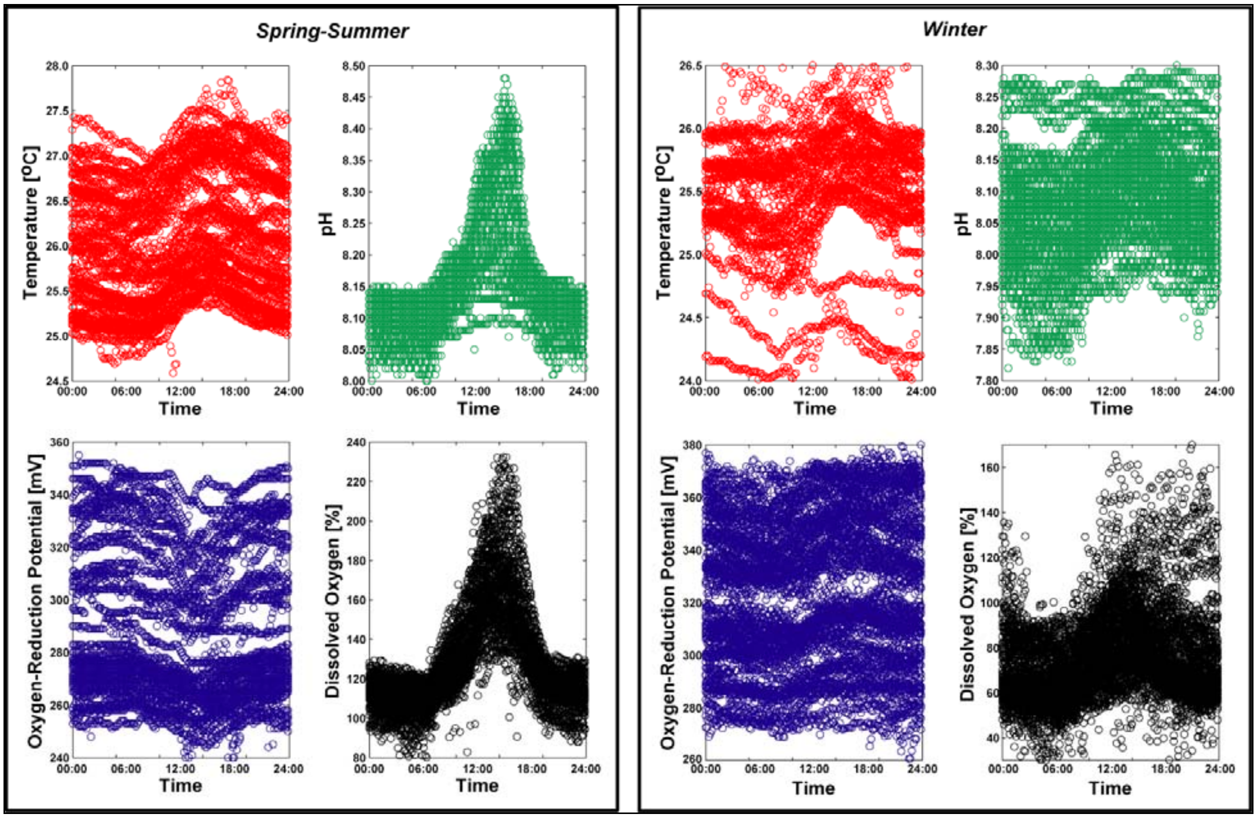

Figure 4.11. Phasing of pH, oxygen-reduction potential and dissolved oxygen relative to the time of day. These plots show how pH, dissolved oxygen and oxygen-reduction potential increase towards early afternoon and decline through the night into the early morning.

insolation-driven warming or insolation-driven Trade wind intensification and Trade-wind wave-induced mixing.

Vertical Variability

The temperatures during the vertical profiles taken in the early morning varied between 27.83 °C and 28.72 °C, with the near-surface temperatures on average roughly 0.74 °C warmer than the near-bed temperatures. The salinities during these profiles varied between 33.47 PSU and 34.38 PSU, with the near-surface temperatures roughly 0.79 PSU less saline on average than the near-bed salinities. The dissolved oxygen levels during these profiles varied between 15.3% and 91.2%, with the near-surface dissolved oxygen levels on average roughly 41.1% higher on average than the near-bed dissolved oxygen levels (Figure 4.12). The temperatures during the vertical profiles taken in the late afternoon varied between 27.85 °C and 29.51 °C, with the near-surface temperatures roughly 1.32 °C warmer on average than the near-bed temperatures. The salinities during these profiles varied between 33.21 PSU and 34.35 PSU, with the near-surface temperatures roughly 0.91 PSU less saline on average than the near-bed salinities. The dissolved oxygen levels during these profiles varied between 11.7% and 104.4%, with the near-surface dissolved oxygen levels roughly 46.6% higher on average than the near-bed dissolved oxygen levels (Figure 4.12).

While mean near-bed temperatures did not vary significantly between the early morning and late afternoon vertical profiles, it is quite apparent that not only did the mean near-surface water temperatures increase significantly, but that a thermocline stretching to 6 m below the surface warmed on average approximately 0.8 °C. Neither salinity nor dissolved oxygen showed significant variations in the mean vertical profiles taken in the early morning versus those taken in the late afternoon.

DISCUSSION

Water movement and water column properties combine to affect steel hull corrosion. Water movement contributes to increased steel corrosion through at least two mechanisms: mechanical abrasion and causing increased dissolved oxygen in the disturbed water. The water movement data collected during this study suggest that the prevailing weather patterns, diurnal tides, and small, long-period swells that dominate Pearl Harbor likely have no extraordinary effects on hull corrosion. The anomalous, high-amplitude, short-period modulations from the southeasterly (90º-150º) or northwesterly (270º-330º) directions, however, may differentially affect *Arizona*'s hull. These swells are likely due to large vessels or possibly Navy tour boats moving past the Memorial, and may contribute to the increased deterioration and corrosion rates noted on the upper parts of the hull, in shallow water (see Chapter 5). As indicated by the corrosion data, due to hull orientation, these anomalous waves have a greater impact on the port side of the hull than the starboard side. In addition, greater current speed on the surface relative to the near bottom also contributes to increased corrosion in the shallower water (see Figure 4.3). The vertical velocity shear, caused by moving seawater of a given density, also imparts a vertical variation in current-induced force on the hull that is relatively greater on the port side than the

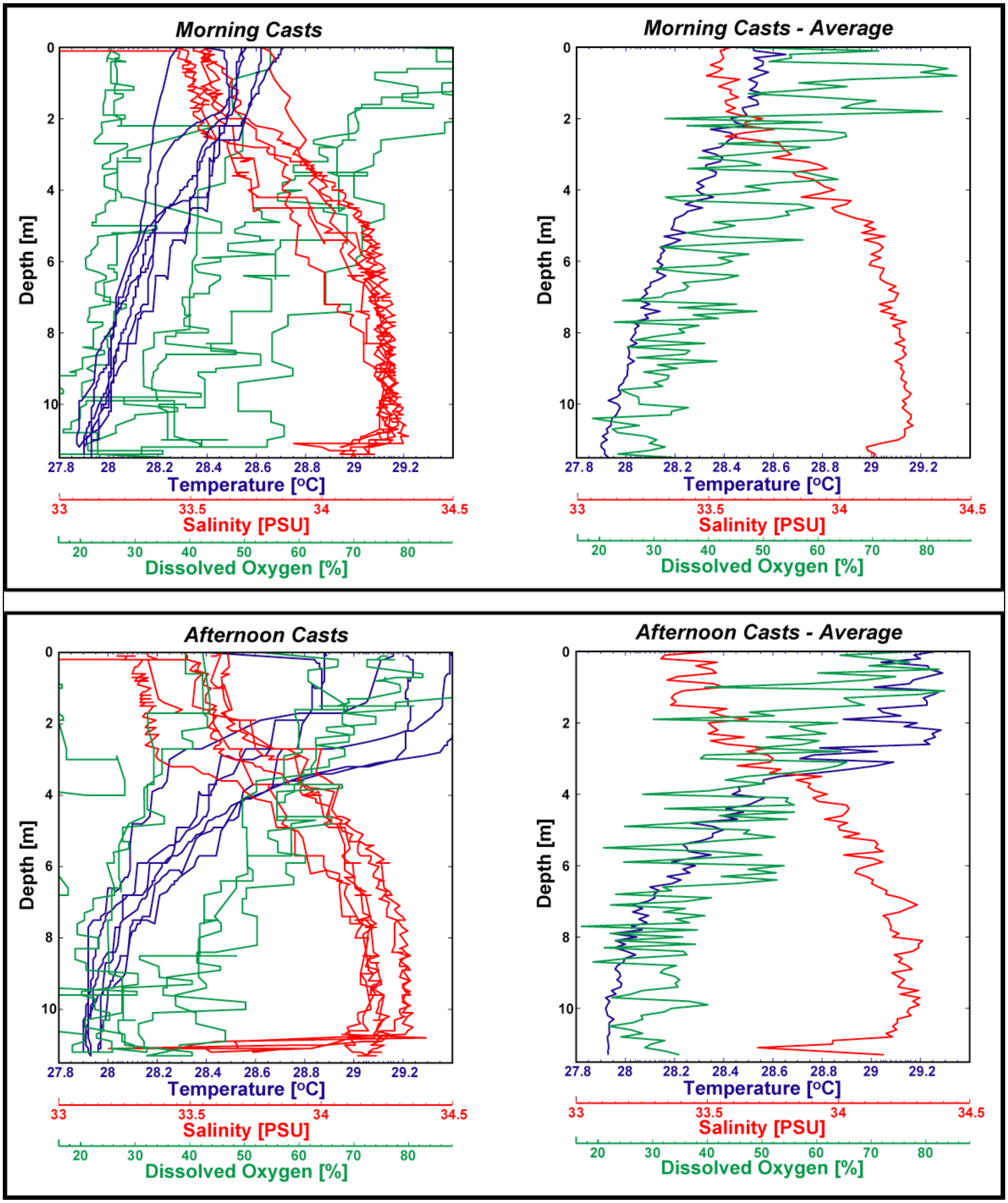

Figure 4.12. Vertical profiles of temperature, salinity and dissolved oxygen off the USS *Arizona* dock. These plots show how these parameters vary vertically from just below the water's surface down to the sea floor and how the vertical variation in these parameters changes over the course of a day.

starboard side of the ship (see Figure 4.4). This vertical velocity shear is also reflected in the corrosion data, with hull metal loss greatest on the port side between the surface and approximately 20 ft. water depth, based on direct measurement of midship hull samples. This differential corrosion is consistent with greater flow velocities on the port side. Below approximately 20 ft. water depth, metal loss is nearly the same on both sides of the hull.

With regard to the second variable, water column properties, it is unknown if acoustic backscatter has any direct effect on hull corrosion, but backscatter is likely a by-product of forces that do have an effect, such as current and other water movement. Water temperature in Pearl Harbor is consistently greater near the surface than near the seafloor, which contributes to the higher corrosion rates measured in shallow water. The temperature difference between the port and starboard sides of the ship is small enough that it likely has no effect on differential corrosion. Salinity, pH, oxygen-reduction potential, and dissolved oxygen vary somewhat over the course of each day and throughout the year, but the long-term data from the YSI Sonde does not offer any comparative data that might address hull corrosion variability. Vertical variability recorded during vertical profiling with the YSI Sonde and dissolved oxygen meter, however, is more illuminating. Corroborating the long-term data recorded with the SonTek ADV and YSI Sonde, temperature was found to be warmer at the surface and cooler near the harbor bottom. In an expected inverse relationship with temperature, salinity was slightly lower at the surface and higher near the bottom. The most important factor recorded, however, is dissolved oxygen, which was found to be on average 41–46% higher near the surface than at the harbor bottom. This strongly contributes to the higher corrosion rates found in shallower portions of *Arizona*'s hull. To determine if the same vertical variability in water column properties occurs inside *Arizona*'s hull as outside of it, comparative interior measurements were recorded. These are discussed in the next section.

INTERIOR DATA COLLECTION

INTERIOR MEASUREMENTS, 2002-2004

Environmental monitoring was conducted within *Arizona*'s interior cabins to determine internal environmental conditions. Internal conditions can be compared to external conditions to infer interior corrosion nature and rate. These data are critical to developing a viable Finite Element Model that takes into account both interior and exterior hull corrosion. Interior investigations began in 2002 and used an YSI dissolved oxygen meter to obtain dissolved oxygen concentration inside selected core drill holes after removal of steel hull samples (see Chapter 5 for details of core sample operations). Investigations of interior spaces in 2003 used a VideoRay Remotely Operated Vehicle (ROV) equipped with a YSI 600XLM Multiparameter Sonde (a smaller version of the YSI Model 6600 Sonde described above) to measure temperature, salinity, pH, dissolved oxygen, and oxygen-reduction potential—with the exception of acoustic backscatter, the same parameters recorded externally (Figures 4.13 and 4.14). This survey focused on second deck cabins accessible to the ROV via open portholes, as well as inside Barbette No. 3, which is accessible from the surface. Subsequent investigations in 2004 recorded environmental parameters in Third Deck spaces—although very few of these areas were accessible to the ROV.

Operations

Interior Dissolved Oxygen Measurements, 2002

An YSI dissolved oxygen meter was used to obtain dissolved oxygen concentration inside selected core drill holes after removal of steel hull samples during 2002 sampling operations. First, ambient seawater was measured on the exterior of the sample location. Next, the dissolved oxygen probe was attached to the end of a 6 ft. section of PVC pipe and inserted into the hole after removal of a plug seal, which had been inserted into each drill hole after the core was removed. The probe was inserted 1–2 ft. and the readings were allowed to stabilize before recording. A total of five locations were sampled in this way.

Interior ROV-based Measurements, 2003–2004

For ROV operations in 2003–2004, the YSI Sonde was used in profiling mode to take continuous measurements. The VideoRay ROV manufacturers integrated the YSI Sonde with the ROV so that data could be received on the surface from the Sonde through the ROV tether,

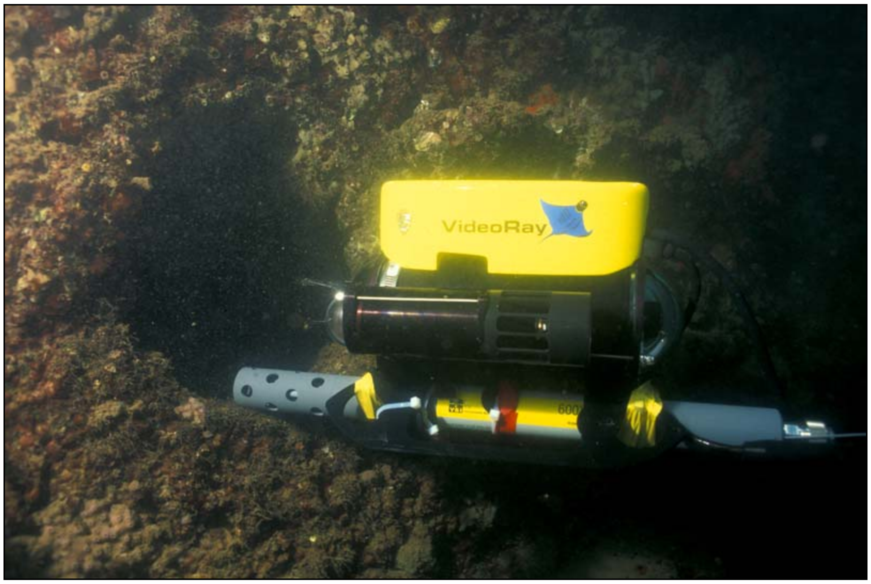

Figure 4.13. VideoRay ROV equipped with YSI Sonde outside on open porthole on USS *Arizona*'s Second Deck (NPS Photo by Brett Seymour).

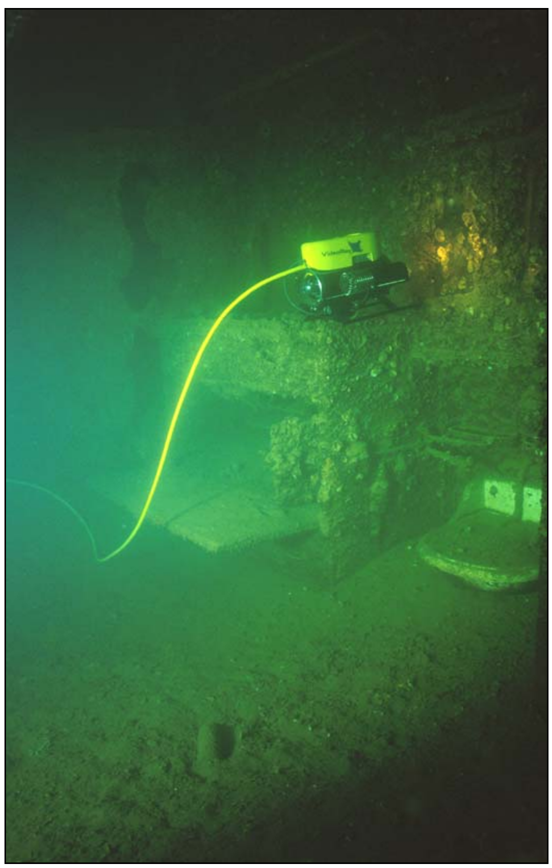

Figure 4.14. VideoRay ROV conducting interior investigations on USS *Arizona*'s Second Deck (NPS Photo by Brett Seymour).

and the Sonde could be controlled from the surface via a laptop computer. This allowed researchers to record separate data files for each location sampled. In addition, a continuous log of ROV movements was recorded and the timestamp on the ROV video could be correlated with the timestamp on the YSI data stream to allow precise interpretation of ROV location within each cabin.

In total, 23 separate interior spaces were measured using the YSI Sonde-equipped VideoRay ROV. These spaces included 20 cabins and hallways on the Second Deck accessible through a combination of open portholes, exterior hatches, and accessible bulkheads; two interior spaces on the Third Deck that are only accessible via vertical hatches, including one that can only be reached after a long run down a Second Deck hallway; and the interior of Barbette No. 3, which reaches down to the First Platform level (just below the Third Deck) (Figure 4.15).

Results

Interior Water Column Properties

Interior water column properties collected include variations in temperature (ºC), salinity (PSU), pH, oxygen-reduction potential (mV), and dissolved oxygen (%). Their ranges, variability and potential causes for their variability are discussed here. In total, 9,203 measurements were taken from Second Deck spaces; 2,160 measurements from Third Deck spaces, and 423 measurements at the First Platform level of Barbette No. 3.

Temperature

Temperatures recorded in Second Deck cabins varied from 26.3–27.5ºC, with an average of 27.2ºC; on the Third Deck, temperatures were steadier at 27.3–27.5ºC with a 27.4ºC average; inside Barbette No. 3 at the First Platform level, water temperatures were slightly cooler, ranging from 24.7ºC to 26.7ºC, with an average of 26.6ºC. All interior temperatures fall within the seasonal and/or daily range of variability recorded on *Arizona*'s exterior.

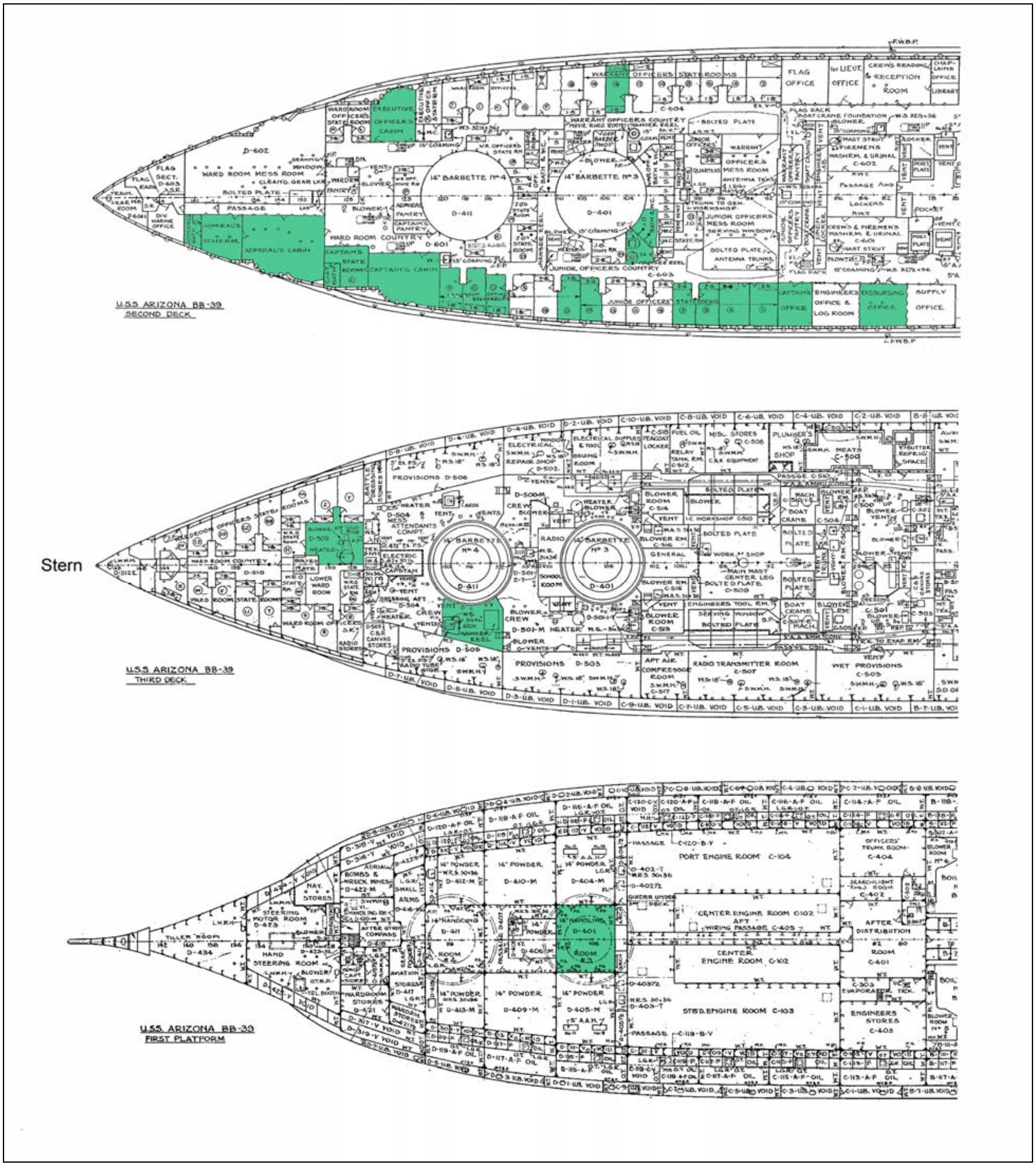

Figure 4.15. Interior spaces measured using the YSI Sonde-equipped VideoRay ROV.

Salinity

Inside Second Deck cabins, salinity ranged from 31.1–35.1 PSU, with an average of 34.0 PSU; on the Third Deck, salinity was 30.2–32.4 PSU with a 32.2 PSU average; inside Barbette No. 3 at the First Platform level, salinity was slightly higher (likely due to less seawater exchange and evaporation from the open top of the barbette), ranging from 35.3–35.0 PSU, with an average of 34.3 PSU. Like temperature, all interior salinity measurements fall within the long-term range of variability recorded outside *Arizona*'s hull, although the more enclosed Third Deck has a salinity that is slightly under 2 parts per thousand lower than more exposed interior spaces.

pH

Within Second Deck cabins, pH varied from 7.05–9.36, with an average of 7.69; on the Third Deck, pH was steadier at 7.90–8.07 with a 8.01 average; inside Barbette No. 3 at the First Platform level, pH was slightly higher, ranging from 8.18–9.36, with an average of 8.41. All interior pH measurements are close to the seasonal and/or daily range of variability recorded on *Arizona*'s exterior, and are within the normal range of variability for seawater, although enclosed interior spaces have slightly higher pH levels.

Oxygen-Reduction Potential

Oxygen-reduction potential recorded in Second Deck cabins varied from 125–912 mV, with an average of 775 mV; on the Third Deck, oxygen-reduction potential readings were anomalous, ranging from -237–307 mV with a -129 mV average; inside Barbette No. 3 at the First Platform level, oxygen-reduction potential ranged from 281–733 mV with a 642 mV average. Oxygen-reduction potentials fall well outside the seasonal and/or daily range of variability recorded on *Arizona*'s exterior, and (with the exception of the Third Deck readings) are much higher on average (see Chapter 5 for a more extensive discussion of oxygen-reduction potential)

Dissolved Oxygen

The data from interior dissolved oxygen measurements through hull steel sample holes taken in 2002 are shown in Table 4.5. Exterior measurements in ambient seawater before inserting the dissolved oxygen meter into the hull varied from 4.74 to 5.68 mg/L (Note: mg/L is an alternative unit of measure for dissolved oxygen, but one not easily converted to percent saturation after the fact). Once inserted into the hull through the core sample holes approximately 1–2 ft., the readings dropped, varying between 0.0 and 3.99 mg/L once they stabilized. These interior spaces reveal a wide range of oxygen concentrations depending upon access to ambient seawater. For the sample locations on the second deck (USAR-02-002 and USAR-02-008), which have some seawater exchange through open port holes, dissolved oxygen concentration dropped an average of 27% below ambient, exterior seawater measurements. For the sample locations in the torpedo blisters (USAR-02-003, USAR-02-004, and USAR-02-009), the dissolved oxygen concentration varied from 2.47 to 0.0 mg/L depending on proximity to breaches in the otherwise sealed torpedo blister, 56–100% less than ambient exterior measurements. Dissolved oxygen levels dropped to zero or near-zero in the two locations where the torpedo blister was completely sealed and had no seawater exchange.

From the YSI Sonde-equipped VideoRay ROV, inside Second Deck cabins dissolved oxygen ranged from 45.0–104.1%, with an average of 64.0%; on the Third Deck, dissolved oxygen levels were 0.0–12.6% with a 4.1% average; inside Barbette No. 3 at the First Platform level, dissolved oxygen was 40.4–80.6%, with an average of 47.8%. Interior dissolved oxygen measurements fall within the long-term range of variability recorded outside *Arizona*'s hull, although the Third Deck has much lower dissolved oxygen saturation than other interior spaces. In general, dissolved oxygen saturation decreases significantly as active seawater exchange is reduced. This observation is significant when considering interior steel hull corrosion rates.

Sample Number	Location	Exterior DO (mg/L)	Interior DO (mg/L - lowest)
USAR-02-002	Second Deck - Limited Seawater Exchange	4.74	3.99
USAR-02-003	Torpedo Blister - No Seawater Exchange	5.52	0
USAR-02-004	Torpedo Blister - No Seawater Exchange	4.82	0.01
USAR-02-008	Second Deck - Limited Seawater Exchange	5.4	3.35
USAR-02-009	Torpedo Blister - Limited Seawater Exchange	5.68	2.47

Table 4.5. Dissolved oxygen measurements inside the hull steel sample core holes.

Vertical Variability

One of the more interesting observations is that interior cabin water on the Second Deck is stratified by a subtle thermocline of about 0.2ºC. Dissolved oxygen levels, however, change significantly across this thermocline, from nearly 70% saturation above to about 50% saturation below the thermocline. This observation was noted throughout all Second Deck cabins. Although interesting, this phenomenon likely has a negligible effect on overall corrosion, and the observation was not repeated on the Third Deck at the First Platform level.

DISCUSSION

Except for dissolved oxygen and oxygen-reduction potential, water column properties from interior spaces of USS *Arizona* vary only slightly from exterior conditions. In general, Second Deck measurements vary little from Third Deck measurements. The amount of variation observed is considered negligible for all variables, with the single exception of dissolved oxygen. Interior measurements of temperature, salinity, and pH all fall within the seasonal or daily variation recorded on *Arizona*'s exterior and the norms expected for Pearl Harbor seawater. Salinity was slightly less on average in the lower, more enclosed portions of the hull's interior, while pH slightly higher; both of these would contribute to slightly lower corrosion rates. Significant differences in dissolved oxygen were observed on the hull's' interior, however, compared to baseline measurements outside the ship. As mentioned previously, dissolved oxygen is also the most important variable contributing to steel corrosion in seawater (see Chapter 5), and this is therefore a significant observation. The higher overall oxygen-reduction potential measurements may reflect lower overall active corrosion, which would be consistent with other observations.

CONCLUSION

In all, more than 1,000,000 external observations of currents, waves and water-column properties were collected per day for 393 days between November 2002, and April 2005, in Pearl Harbor. Significant findings based upon these measurements and analyses include:

(1) Tides are of mixed, semi-diurnal type with a minimum, mean and maximum tidal range of 0.4 m, 0.6 m and 0.9 m, respectively.

(2) Waves are not an important factor in the vicinity of USS *Arizona*'s hull. Those observed were, while long period (~20 s), very small (order of cm's) and likely due to open-ocean long-period swell. Vessels passing close to the study site are likely responsible for the high-amplitude, low-period motions that were observed.

(3) Flow along the 10-m isobath is dominated by semi-diurnal and diurnal tidal motions, which are modulated to some degree by what appears to be wind forcing during the mid- to late afternoon. Flow at the surface is down-wind to the southwest. Flow throughout most of the water column is primarily parallel to the USS *Arizona*'s hull at 0.01-0.02 m/sec and net flow is to the northeast. Flow closer to the seafloor, however, is weaker and more variable in direction.

(4) Flow speeds are faster off the port side than the starboard side, and thus the water replenishment times on the port side of the hull are shorter than off the starboard side. Shear, both vertically in the water column and across the hull, was observed. This results in vertical variations in replenishment times and current-induced forces on the hull. This shear also likely increases vertical mixing of the water column.

(5) Acoustic backscatter was generally higher in the winter months and during the falling tide, suggesting advection of material introduced into the northern sections of Pearl Harbor due to winter precipitation and its movement south past the hull by ebbing tidal currents. Higher measurements of acoustic backscatter often occurred in the afternoon, suggesting increased trade wind-induced mixing or, perhaps, increased vessel activity, which facilitates water column mixing and fine-grained particulate resuspension.

(6) Water temperatures were generally slightly higher (mean = 26.03 °C) and less variable (standard deviation = 1.17 °C) along the 10-m isobath than along the 3-m isobath (mean

= 24.55 °C, standard deviation = 2.08 °C). A thermocline was often present in the harbor's waters, with the shallower (3 m) and deeper (10 m) water temperatures often differing by more than 2 °C. Water temperatures along the 10-m isobath were generally cooler and less variable off the port side of the hull than off the starboard side, possibly due to faster replenishment times and greater mixing of the water column.

(7) Salinity ranged from 16.78 PSU and 42.56 PSU, with a mean ± one standard deviation of 34.33 ± 4.25 PSU. Salinity appears to positively correlate with water temperature and suggests that Pearl Harbor's waters are influenced by freshwater runoff or groundwater effluence in the winter months.

(8) pH ranged between 7.60 and 9.10, with a mean ± one standard deviation of 8.04 ± 0.15 and dissolved oxygen 0% and 288.5%, with a mean ± one standard deviation of 69.5 ± 58.8%. Both pH and dissolved oxygen tended to correlate with the daily insolation cycle, increasing during the morning into the early afternoon followed by decreasing through the night to minimum levels just before sunrise.

(9) Oxygen-reduction potential ranged between 150.0 mV and 397.2 mV, with a mean ± one standard deviation of 289.2 ± 50.6 mV. Oxygen-reduction potential had an *inverse* with pH and the percentage of dissolved oxygen during the summer months and a *positive* relationship with pH and the percentage of dissolved oxygen during the winter months when temperature and salinity were more variable.

(10) During the vertical profiling, near-surface temperatures were on average roughly 1.03 °C warmer than the near-bed temperatures, near-surface temperatures were roughly 0.85 PSU less saline on average than the near-bed salinities and near-surface dissolved oxygen levels were on average roughly 43.9% higher than the near-bed dissolved oxygen levels.

These data provide us with a much clearer picture of the nature of and controls on the physical environment around USS *Arizona*'s hull. The complexity of the physical environment surrounding and influencing *Arizona* is reflected in the number of interesting phenomena observed during this study. The next step is to correlate these environmental aspects with active corrosion processes affecting *Arizona* to refine the predictive model of the ship's deterioration.

On *Arizona*'s interior, in general, most parameters recorded with the YSI Sonde-equipped VideoRay ROV were very similar inside the ship as outside. Temperature, salinity, and pH were all within a normal range of variability. Dissolved oxygen and oxygen-reduction potential, on the other hand, varied significantly from baseline measurements outside the hull. The most significant observation is that dissolved oxygen decreased to near-zero within interior spaces that do not receive active seawater exchange. Most significantly, on the Third Deck, which has no direct access to exterior seawater except through a single vertical hatch, dissolved oxygen averaged only 4.1% saturated. With the exception of a small portion of the First Platform accessible through Barbette No. 3, there is no access to any interior spaces below the Third Deck. However, based on data from the Third Deck and within the torpedo blisters, which indicate that dissolved oxygen can reach 0.0% saturated in spaces that do not have seawater exchange, it is probable that *Arizona*'s interior spaces below the Third Deck have extremely low levels of dissolved oxygen, and may even be at 0.0% saturated. Because all of *Arizona*'s original oil storage spaces are below the Third Deck, and the majority of *Arizona*'s remaining oil is likely still stored in those spaces, it is probable they are undergoing very low corrosion rates. This topic will be discussed in more detail in Chapter 5.

REFERENCES

National Climate Data Center, National Oceanographic and Atmospheric Administration
2005 NCDC Hourly Surface Climate Data for Hawaii, Online Dataset, http://www.ncdc.noaa.gov/oa/climate/climatedata.html#hourly

North, N. A. and I. D. MacLeod
1987 Corrosion of Metals. In *Conservation of Marine Archaeological Objects*, edited by C. Pearson, pp. 68-98. Butterworth & Co., London.

Storlazzi, C. D., M. A. Russell, M. D. Owens, M. E. Field and L. E. Murphy
2004 *Dynamics of the Physical Environment at the USS Arizona Memorial: 2002-2004*. U.S. Geological Survey Open-File Report 2004-1353, http://pubs.usgs.gov/of/2004/1353/.

Storlazzi, C. D., M. A. Russell, M. K. Presto and J. E. Burbank
2005 *Flow Patterns and Current Structure at the USS Arizona Memorial: April, 2005*. U.S. Geological Survey Open-File Report 2005-1334, http://pubs.usgs.gov/sir/2005/1334/.