SCIENCE AT THE CROSSROADS: THE NAVY, BIKINI ATOLL AND AMERICAN OCEANOGRAPHY IN THE 1940S

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In the summer of 1947 some fifty scientists, accompanied by an equal number of navy personnel, descended upon Bikini Atoll in the Marshall Islands of the western Pacific. They came armed not with weapons, but with an array of scientific instruments and equipment, including fathometers, sonar, and underwater cameras, as well as ships, trucks, and amphibious vehicles. The objective of this Bikini Scientific Resurvey, as it was called, was to assess the effects of Operation Crossroads, the atomic bomb tests that had taken place at Bikini the previous year.1

The expedition's activity that received the most attention was the effort to drill deep holes into the subsurface of Bikini Island. Frequent navy dispatches kept the press and public apprised of those efforts, which eventually resulted in a world drilling record that surpassed 2,500 feet. The objective of the drilling operation was to solve a longstanding scientific problem: the formation of atolls. In the 1840s Charles Darwin had advanced the theory that atolls were formed by coral growing upward and forming reefs around a slowly sinking volcano. Over the next century Darwin's theory generated considerable debate, but as Roger Revelle, director of the Bikini Resurvey stated, it was now hoped that core samples taken at Bikini might "prove whether or not Darwin was right."2

Work done at Bikini, and later other atolls in the Marshall Islands, did confirm Darwin's theory.3 Nevertheless, the question remains, why would the navy support work on such a strictly scientific question? The navy did not have an immediate interest in the solution of the coral reef problem; both the military and scientists understood it within a broader context. That understanding was the product of specific historical circumstances developed during World War II between the navy and scientists interested in the physics and geophysics of the oceans. While the government had provided some support for oceanography in the 1920s and 30s, it was only with the onset of war that oceanography became a topic of vital interest to the navy. Military leaders had limited interest in the science itself; rather oceanography became important for the role it could play in subsurface and amphibious warfare. Other studies have indicated how military technological and operational needs influenced science during and after World War II.4 This paper, while paying attention to those issues, will also suggest that strategic and geopolitical interests played a part in the support for oceanography. During the 1940s military patronage helped redefine the role and objectives of American oceanography; as a result, the study of coral reefs, a topic of theoretical inquiry before the war, took on new and additional meanings.

The Navy and Oceanography Before World War II

The navy has had a long history of supporting science. In the nineteenth century the navy backed the United States Exploring Expedition, and in later years promoted Matthew Fontaine Maury's pathbreaking work in physical oceanography. During World War I the Naval Consulting Board sponsored efforts to develop underwater listening devices, and in the 1920s the Naval Research Laboratory (NRL) included several scientists, most notably Harvey C. Hayes, who studied underwater sound. In those years Hayes developed an improved sonic depth finder as well as a viable echo ranging (sonar) system. He also spearheaded an effort, which included scientists from several government agencies, to establish an oceanographic office within the navy. That effort failed for lack of financial support, but Hayes and his colleagues continued their investigations and experiments on echo ranging instruments. Their work emphasized improving the equipment and devoted little attention to understanding the medium within which the equipment operated.5

The navy also showed some interest in the principal oceanographic centers in the United States: the Scripps Institution of Oceanography (SIO) in La Jolla, California, and the Woods Hole Oceanographic Institution (WHOI) in Woods Hole , Massachusetts. In the 1930s, both were small, isolated institutions, each with staffs of about a dozen people, one ship, and limited research facilities. Both also relied on private philanthropy. SIO, a division of the University of California, received almost half its support from the Scripps family, while the Rockefeller Foundation provided most of the funding for Woods Hole. The navy, by contrast, provided direct sponsorship only for projects to develop anti-fouling methods for protection of ships' hulls.6 It did, however, support those institutions in other ways. The directors of WHOI and SIO, Henry Bryant Bigelow and Thomas Wayland Vaughan, developed good working relationships with the Hydrographic Office (HO), the principal government agency for the publication of navigational guides and charts worldwide. Through arrangements with the Navy Hydrographer, Rear Admiral Walter R. Gherardi, that agency provided both institutions with seawater temperature, salinity, and dynamic sounding data. The Hydrographic Office also allowed Scripps' scientists to conduct research onboard its vessels, and in the 1930s two graduate students, Richard H. Fleming and Roger Revelle, spent several months collecting data in the Caribbean and Pacific.7

While the Naval Research Laboratory and the Hydrographic Office supported work on sonar and navigation, opportunities for science in the navy remained limited. To the navy the oceans were the environment in which its forces operated, and an emphasis on operational doctrine and engineering dominated. In the 1930s, when the navy co-sponsored an expedition to measure gravity at sea, it was primarily interested in staying abreast of any new technological developments related to the oceans.8 The Hydrographic Office permitted its crews to assist the oceanographic institutions by gathering data and taking soundings, but only as "a side line, . . . because of the difficulty of diverting ships or men from other jobs." When Bigelow and Vaughan requested additional commitments, including a ship exclusively for oceanographic work, the navy declined.9

Oceanographers, by contrast, defined their field broadly. Vaughan and Bigelow, for example, did not consider oceanography a specific discipline. Rather it was the study of a particular place, the oceans, and oceanographers employed the knowledge, techniques and methods from geology, biology, physics, and chemistry to study that medium. They were well aware of the practical and commercial aspects of the science and pointed out how oceanography could contribute to the search for oil, development of fisheries, and weather forecasting. Yet in 1936 even Revelle, who had spent two summers onboard navy vessels and become an officer in the Naval Reserve, admitted that he had difficulty defining how oceanography could contribute to the navy's operational objectives.10

The relationship between the navy and some oceanographers began to change in the late 1930s following tests of the new echo ranging systems. Experiments onboard the U.S.S. Semmes in Guantanamo Bay yielded a high percentage of missed targets. Unable to determine any problem with the instruments, the commanding officer of the Semmes, acting on the advice of NRL director Rear Admiral Harold G. Bowen, contacted scientists at Woods Hole. In 1937 Columbus O'Donnell Iselin identified the source of the problem as what he termed "the afternoon effect": the impact that diurnal conditions, specifically the changing temperature of sea water, had on underwater sound transmission. Additional studies, often conducted on the Semmes, at Guantanamo Bay, New London, Connecticut over the next two years confirmed those findings and laid the foundation for important changes in the relationship between the navy and oceanographers.11

Prior to Iselin's work few scientists had studied problems of underwater sound transmission. Physicists rarely had access to the equipment necessary for such investigations. Nor had the subject attracted the attention of oceanographers. In the 1920s and 30s American oceanographers became increasingly interested in physical oceanography, including the new dynamical studies coming out of Norway. At Woods Hole Bigelow, Iselin, and Edward Smith studied the works of Vilhelm Bjerknes, and in 1936 Harald Sverdrup, a student of Bjerknes and a leading physical oceanographer in his own right, emigrated from Norway to become the new director of Scripps. But those developments did not immediately lead to research on underwater sound. Sverdrup's first investigations at SIO, studies of water circulation off the California coast, followed the methods of dynamical oceanography. He and Fleming analyzed currents, circulation patterns, and upwelling in relation to other oceanographic and meteorological factors. They did not study underwater sound transmission. Iselin's early researches were similar, until work with the navy led him in a new and different direction.12

Iselin pursued opportunities in that new field on several fronts. He expressed interest in the work of Maurice Ewing, a geophysicist at Lehigh University who was using explosives for underwater sound tests. In the hands of geophysicists seismic refraction studies constituted an important tool in the search for oil; for Ewing they were a means for examining the earth's structure beneath the sea. Although Bigelow hesitated when Ewing asked permission to carry out such tests at WHOI, Iselin recognized an additional means for studying underwater sound transmission and by 1940 Ewing was a member of the staff.13 Iselin's initiative also stimulated instrument development. In 1938 WHOI scientist Athelstan Spilhaus built what he called a bathythermograph (BT), an instrument capable of recording underwater temperature as a function of depth. Iselin's research had defined temperature and pressure as the two main variables influencing underwater sound transmission, and the BT became the instrument for studying the behavior of sound in seawater.14

Research on underwater sound required access to sonar, submarines, and surface vessels, and Iselin developed good relations with the NRL, the Bureau of Ships, and the submarine command at New London. For the navy, especially the NRL and the Bureau of Ships, the operational performance of echo ranging equipment, namely its capability of detecting submarines, was the top priority. Iselin and Ewing's efforts convinced navy officers that the BT could improve sonar performance, and by 1940 the scientists were taking part in sonar tests onboard the Semmes, training navy ensigns in the use of the BT at Woods Hole, and manufacturing the instrument.15

WHOI's close relationship with the navy did not extend to oceanographers elsewhere. The Navy Fleet Sound School, one of the main facilities for testing sonar systems and sonic depth finders, was located at Point Loma, California, only fifteen miles from SIO. The two organizations, however, had only limited interaction. In 1939 the officer in charge of the Sound School, Captain A.D. Burhans, requested ocean temperature, pressure, and salinity data from SIO. The next year Burhans arranged for Revelle to spend one week onboard the U.S.S. Rathburne, where he participated in underwater sound transmission exercises. But Burhan's unit had difficulty obtaining BTs from WHOI or the navy, and when Revelle returned to Scripps after one week of Naval Reserve duty, he could not discuss underwater sound equipment or tests with his civilian colleagues. In October 1940, when Burhans suggested to the navy that the Sound School, SIO, and another nearby facility, the Navy Radio and Sound Laboratory (NRSL), establish a cooperative project on underwater sound, the proposal fell on deaf ears. Iselin would complain that the navy showed more interest in developing instruments than supporting research on underwater sound, nevertheless a unique relationship had developed between navy officers and Woods Hole oceanographers.16

That situation would soon change. By 1940 the threat posed by German submarines and the increasing possibility of war lent greater urgency to subsurface warfare. With unrivalled access to the navy, Iselin understood how his work on underwater sound could contribute to that effort. Yet Iselin, aware that NRL lacked a commitment to research, also maintained that navy bureaucracy and operational emphases presented obstacles to new initiatives. In the fall of 1940, while continuing work with the navy, he negotiated a contract for research on underwater sound with the new civilian scientific agency, the National Defense Research Committee (NDRC). He also contacted Frank B. Jewett about his concerns. Jewett, then president of the National Academy of Sciences, called for the creation of an academy committee to investigate the navy's work and explore a wide range of questions pertaining to underwater sound transmission and subsurface warfare.17

That committee, known as the Colpitts Committee for its chair, Edwin H. Colpitts, issued a report critical of the navy's efforts. While Colpitts and his colleagues, William Coolidge, Vern O. Knudsen, and Louis Slichter, praised NRL's pathbreaking work on sonar, they pointed out that the equipment worked effectively only 50% of the time. Noting that NRL scientists had experimented exclusively with supersonic equipment, the committee recommended additional work on low frequency sound. Most important, Colpitts and his colleagues emphasized the need for fundamental research.18 Not suprisingly, the report provoked reaction within the navy. Bowen wrote to Jewett in protest, claiming that existing equipment was efficient, experimentation with audible frequency equipment would not work, and scientists on the committee had not been objective. Rear Admiral A. H. van Keuren concurred. But Secretary of the Navy Frank Knox supported the report, and in April 1941 the navy agreed to work closely with a new Division 6 of the NDRC, the project on subsurface warfare.19

The Navy, the NDRC, and Oceanography During World War II

Based on the Colpitts Report, leaders within the NDRC and the navy created laboratories throughout the country for work on underwater sound. The NDRC, which had already entered into a contract with Woods Hole, now established a special studies group devoted to sonar analysis in New York. Harvard University became the site for an underwater sound laboratory, and two new laboratories were created at opposite ends of the country: the Columbia University Division of War Research (CUDWR) and the University of California Division of War Research (UCDWR). As the names suggest, the laboratories had affiliations with their respective academic institutions. In addition, both were located at military installations and had close ties to the navy: CUDWR at a Coast Guard facility at Fort Trumbull, New London, Connecticut, in close proximity to the Navy Submarine Base; and UCDWR on the grounds of the NRSL in Point Loma, California.20 As a result of negotiations between the navy and the NDRC the civilian laboratories would function as centers for research on underwater acoustics and design and construction of underwater sound equipment. The navy had responsibility for all testing and development of such equipment and weapons. But there was considerable overlap, and even though Rear Admiral Julius A. Furer, the navy's Coordinator of Research and Development, mediated activities between the two organizations, controversies occurred. From October 1941 through August 1942, a series of disputes disrupted the relationship between UCDWR and the NRSL. Negotiations eventually solved that problem, and in general a good working relationship developed between the navy and the NDRC. It was, however, a relationship that significantly changed oceanography.21

With the establishment of large scale, multi-faceted projects on subsurface warfare, the study of the oceans now became the province of more than just a handful of oceanographers. The need to understand the ocean environment and to design, test, and manufacture instruments and weapons for fighting a war in that environment required a wide range of specialists. The development of a staff at UCDWR, for example, entailed transferring Fleming, Francis P. Shepard, and other oceanographers from Scripps. The need for physicists and engineers was even more important. As the principal facility for fundamental research on underwater sound, the UCDWR staff, headed by Knudsen, included the physicists Edwin McMillan, Henry Hartig, and Franz Kurie. Carl Eckart, a University of Chicago physicist who declined to work on the Manhattan Project, directed research on underwater sound.22 Other scientists and technicians were recruited to design new sonar systems, sono-radio buoys, and harbor protection devices. Since those instruments could be tested only under military auspices, civilian scientists and engineers worked closely with the navy and its contractors to manufacture and mass produce such equipment. Oceanographers and physicists also worked onboard ships and submarines training navy operators in the use of the BT, sonar, and other equipment.23 At UCDWR and elsewhere, oceanographers entered into a new and different culture, one that required learning navy rules, language, and operations, and emphasized the priorities associated with subsurface warfare.24

Oceanographers had long relied on instrumentation to study an alien environment not accessible by direct observation. In the context of World War II, however, research served the purpose of testing, evaluating, and improving the operational effectiveness of instruments and weapons. Such objectives fostered much scientific investigation, but as

Colpitts, the second in command of Division 6 noted, even fundamental studies were carried out "to understand better the operation of present gear and to be able to design better gear." Lyman Spitzer, one of the chief physicists in Division 6, lamented that sonar analysis was far from actual scientific research, while Eckart admitted to being relieved when the title of projects in his division changed from "fundamental research" to "sonar operations research," since he had actually discouraged fundamental research.25

Those priorities characterized the work done on underwater sound transmission. Equipment performance at sea had first led the NRL to contact Woods Hole in the late 1930s, and equipment performance remained the guiding principle for work on underwater sound in subsequent years. In early 1941 Iselin and Ewing completed a report entitled "Sound Transmission in Sea Water." The study was designed to convince navy officers and scientists that physical factors influenced underwater sound transmission. Emphasizing that sound waves were generally refracted in seawater, the authors indicated how temperature, pressure, and, to a lesser extent, salinity affected the horizontal and vertical velocity of sound. Based on experiments conducted at Guantanamo Bay and Key West, Florida, they demonstrated that behavior of sound waves in seawater varied by location, time of day, and season of the year. Iselin and Ewing wanted support for further scientific research on underwater sound, but they also recognized that their work had to contribute to the navy's practical, operational objectives. Again and again their report highlighted how scientific knowledge, particularly an understanding of conditions that could produce positive or negative vertical velocity gradients, had consequences for echo ranging performance. When NRL and the Bureau of Ships agreed to support a program of research, it was largely because

Iselin's two years' experience walking the halls in Washington and the decks of navy vessels had taught him how to sell science to the navy on the navy's terms.26

The development of slide rules and sound ranging (sonar) charts illustrates the same point. During 1941, as the navy installed BTs on ships in the Atlantic and Pacific, scientists at WHOI and UCDWR started receiving thousands of BT slides. Oceanographers at both institutions began considering means for computing echo ranges and making echo range predictions from BT data. Independently, Ewing at WHOI and Revelle and Fleming at Point Loma developed slides rules for that purpose. By early 1942 they were also constructing charts showing sound ranging conditions in strategic locations. The differences between the two slide rules were minimal, but both the navy and NDRC recognized the importance of having only one instrument and one standardized chart. When conferences between the oceanographers failed to produce a compromise or an agreement on which slide rule to use, other scientists were called in to adjudicate. Ewing's circular slide rule became the instrument of choice, but that was not the sole issue at hand. Sonar and the BT had stimulated research and invention, but for the navy operational objectives were the top priority. Standardization of the slide rule and sound ranging charts was necessary since their primary purpose was to inform ships' officers and sonar operators whether conditions were good for detecting or evading submarines.27

The development of BT prediction manuals served the same objective. As Oreskes's paper (this volume) indicates, BT studies led scientists to a more refined understanding of the thermocline, layer effect, and other features of underwater acoustics. For the navy it was especially important to apply that information for use in tactical operations. Scientists at WHOI and UCDWR compiled BT prediction manuals describing how different ocean conditions influenced such tactical parameters as: maximum range of prediction (the greatest distance at which a submarine can be detected); assured range (the maximum range on a submarine at the most unfavorable depth for detection); and the maximum echo range on a submarine at the surface (periscope depth range) or below the surface (evasive range). After 1942, information about sound ranging conditions became increasingly important for a new dimension of submarine warfare: knowing under what conditions submarines could hide.28

Improving sonar performance also promoted the study of ocean bottom sediments. Before the war, Vaughan, Revelle and others had collected bottom sediments to understand submarine topography and marine geological processes. The development of the sonic depth finder, coupled with financial support from petroleum companies, promoted that work.29 During the war the study of ocean bottoms became important in relation to underwater acoustics. While sound waves were usually refracted in sea water, bottom reflections were a complicating factor, especially in shallow water conditions. In 1942 Iselin and others laid out a program for the study of bottom sediments and construction of bottom sediment charts. Sediment analyses and acoustical tests by scientists at WHOI and UCDWR yielded a classification system that described how sound was absorbed, reflected, or reverberated by different sediments and bottom conditions. Bottom sediment charts, Iselin noted, were valuable "for range predictions and . . . are therefore an important part of the general tactical considerations involved in the spacing of vessels and the operation of sonar equipment so as to obtain maximum efficiency. They are equally important to submariners in the latter respect and can also be used in choosing favorable operating areas."30

A knowledge of ocean bottom sediments had additional operational significance: detecting the presence of mines in shallow waters. The Navy Bureau of Ordnance and Naval Ordnance Laboratory were particularly interested in the development of echo ranging equipment for that purpose, resulting in the FM sonar system created at UCDWR. The call for additional initiatives on ocean bottoms had some impact on the navy's decision in the fall of 1942 to appoint Revelle to a dual position in the Hydrographic Office and Bureau of Ships. That appointment gave Revelle responsibility for a wide range of activities in naval oceanography. He also served as navy liasion to NDRC activities in subsurface warfare, including bottom sediment studies at WHOI and UCDWR. Writing to Iselin in June 1943, he noted the navy's interest in learning how mines dropped from planes or ships penetrated different ocean bottoms, and to what extent they would undercut those bottoms. Ordnance organizations also wanted to know how underwater currents and wave amplitude on ocean bottoms affected the movement of underwater mines, and whether bottom sediment coloration could be used to camouflage mines.31 The demands of shallow water warfare, especially in the Pacific, intensified the need for studies of ocean bottoms. They also lent increased importance to the oceanographic and geophysical work done at UCDWR and SIO.32

The need for harbor protection likewise promoted work in oceanography. The navy had previously developed various harbor protection instruments, including hydrophones, sono-radio buoys, and magnetic and acoustic cable systems. In contrast to sonar these were passive listening devices for detecting ships, submarines, or weapons introduced into harbors. Traditionally, the navy viewed harbor surveys narrowly: as means to test and determine the best locations for equipment. In February 1942 John T. Tate, the chair of Division 6, suggested to Vannevar Bush that the surveys required better definition and inclusion of fundamental research. Administrators in the navy and NDRC agreed, and work in Puget Sound and San Francisco Harbor incorporated oceanographic research. Conducted jointly by UCDWR and the NRSL, those surveys drew upon the scientific expertise of Revelle, Fleming, Francis Shepard, and Eugene LaFond. They examined how oceanographic conditions affected observed and calculated echo ranging conditions. In addition to analyses of ocean bottom composition and topography, the surveys incorporated studies of current velocities on the surface and on bottoms. While some navy officers at Point Loma and New London objected to civilian scientists doing research in what was traditionally navy domain, the views of Tate, Furer, and other administrators prevailed and oceanographic work became a staple of harbor protection operations.33

Oceanography also contributed to amphibious warfare operations. That was especially true in the Pacific theatre where the United States sought to gain control of the islands and atolls of the Japanese mandate. Those objectives required extensive geodetic and oceanographic data. Traditionally, the Hydrographic Office and the Office of Naval Intelligence had gathered information about harbors, ports, and anchorages at strategic locations worldwide. Now, however, amphibious operations called for improvements to and increased use of existing technology. Aerial photography, a technique used since the 1910s, became a vital component in amphibious warfare. The Hydrographic Office established a section for photogrammetry and called upon the Department of Agriculture for stereoscopic plotters for enhancement of island and atoll topography.34 Much of the fighting on islands and atolls entailed use of underwater mines by both sides; consequently, navy operations required detailed information on underwater formations and conditions. Beginning in late 1943, the principal Hydrographic Office vessels operating in the Pacific, the U.S.S. Sumner and U.S.S. Bowditch, conducted dredgings, soundings, and bathymetric profiles at all islands and atolls. Onboard the U.S.S. Cape Johnson, Harry Hess's efforts revealed the presence of flat-topped seamounts 3000 to 6000 feet below sea level. His discoveries, which aroused considerable scientific interest in the coral reef problem, were a product of the military's operational objectives in the Pacific.35

The need for that data, and for experts who could interpret and apply the data for use in military operations, led to increased reliance on oceanographers. That was particularly the case at Scripps. In 1941 when several scientists left Scripps for nearby navy and NDRC facilities, Sverdrup and others in La Jolla continued to work closely with their former colleagues. Sverdrup, appointed consultant to the oceanographic section of UCDWR, collaborated with Fleming to produce the first underwater sound reports from that division. In early 1942 the navy denied Sverdrup security clearance, and for the next eighteen months he and other scientists at Scripps had virtually no contact with the work being done on subsurface or amphibious warfare.36 By mid 1943, however, the situation had changed. There now existed a need to draw upon almost all resources that could aid in the effort in the Pacific. Revelle, well aware of the importance of submarine warfare for the Pacific, and anxious to take advantage of Sverdrup's expertise, recommended that the Hydrographic Office begin producing a new publication: the Submarine Supplements to the Sailing Directions. SIO, which possessed the country's best collection of oceanographic information on the Pacific, could contribute to that effort, and a change in Sverdup's security status made that possible. In the summer of 1943 the Hydrographic Office created a project whereby Sverdrup, in cooperation with scientists at UCDWR, would produce the submarine supplements. Sverdrup's clearance applied only to work with the Hydrographic Office; he could not take part in military tests using sonar, BTs, or the new submarine BTs. However, he could receive information on underwater sound conditions and their relationship to tactical procedures, and with that data he helped compile all the submarine supplements for the Pacific theatre.37

Amphibious warfare stimulated oceanographic work in another area: studies of waves. Scientists had done considerable research on waves prior to the war, but the military now needed additional data and development of predictive models. Understanding and predicting sea, swell, and surf were particularly important for beach landings. Because of the significance that meteorological conditions, especially winds, had for such phenomena, the military placed responsibility for work on the topic in the hands of a Joint Chiefs of Staff Committee on Meteorology. Within that committee, the Weather Directorate of the Army Air Forces (AAF) took the lead by creating a project on surf under the direction of H. R. Seiwell, a WHOI trained oceanographer. In December 1942 the Joint Committee added a subcommittee on oceanography and charged Seiwell with the task of developing means for forecasting sea, swell, and surf. Revelle, who became a member of the subcommittee with his appointment to the Hydrographic Office, quickly raised serious questions about the AAF project. At one of his first meetings, he emphasized the navy's vital interest in oceanography and called for joint navy and AAF responsibility on the project. He pointed out discrepancies between surf predictions compiled by the AAF and those done by the British Admiralty. Revelle also knew that Sverdrup, who had expressed reservations about Seiwell's empirical approach to the problem, maintained that a better method could be developed. By the summer of 1943 the navy had become the sole agency in charge of oceanography, and Revelle arranged for Sverdrup to commence work on sea, swell, and surf forecasting. By the end of the year Sverdrup and his colleague Walter Munk had developed a theoretical model for forecasting sea, swell, and surf, one that navy commanders quickly embraced. Sverdrup and Munk's model became the standard employed by the Hydrographic Office; it was also incorporated into one of the military's most important strategic compilations, the Joint Army-Navy Intelligence Studies.38

Revelle, who oversaw work on surf forecasting, also took charge of another HO project to collect information on beaches, shorelines, and coasts that would aid in amphibious operations. The navy turned to scientists at UCDWR and SIO to undertake studies on slope, composition, erosion, and "trafficability" of beaches and inshore environments. By 1945 the navy was calling on other agencies, such as the U.S. Geological Survey, to transfer scientists with a knowledge of oceanography and geophysics to those laboratories. Scientists there also worked closely with the navy and with engineers from the University of California, Berkeley to determine which locations, which kind of craft, and which surf conditions were best for making landings and securing beachheads.39

World War II thus brought considerable change to American oceanography. Navy interests fostered a wide range of scientific investigations which served primarily to improve instruments and weapons for use in military operations. In contrast to prewar oceanography, which encouraged work in all fields, subsurface and amphibious warfare emphasized physical, chemical, and geological oceanography. Underwater sound, a subject that previously had received no attention, became a top priority. Conversely, biological studies, a mainstay of prewar oceanography, largely disappeared with the exception of analyses of marine animal sounds that affected echo ranging performance.40 The concern for developing predictive models, whether for underwater acoustics or sea, swell, and surf forecasting, reinforced the emphasis on physical science. Wartime activities took oceanographers farther and deeper than they had gone before. While WHOI scientists had sailed out into the Atlantic and Caribbean in the 1930s, their counterparts at SIO had confined their explorations to distances within a few hundred miles of San Diego.41 During the war oceanographers ventured across the seas and under the sea, and in the process considerably expanded their knowledge of the world ocean. The war provided oceanographers with a wide range of new opportunities, but access to such opportunities remained dependent on navy vessels, instruments, and monetary support. By 1945 the navy had emerged as the dominant patron of oceanography, and in the process had redefined the material, economic, and disciplinary features of the science.

The Navy and Oceanography After World War II

As World War II came to an end, a number of navy officers made it clear that they recognized the contributions made by scientists. Leaders within the Bureau of Ships, the Bureau of Ordnance, and the Amphibious Forces all praised the ways in which work in oceanography and geophysics had enhanced their activities. Science and scientists had become valued commodities, and throughout 1944 and 1945 Furer and other navy administrators met with civilian leaders to devise means for retaining scientists and engineers after the war. From the navy's perspective, the need to evaluate new systems like FM sonar and deep submergence submarines and the conditions under they could best be deployed was indispensable. The navy required scientific expertise to assess the threat of new weapons, such as the schnorkel submarine and underwater guided missiles, and to develop effective countermeasures. Based on wartime experience, navy leaders maintained that scientific investigations of conditions and testing of equipment were crucial for the development of new weapons.42

Geopolitical interests were also at stake. The United States had won the war, but now had a vested interest in maintaining a presence in the Pacific and other areas of the world. Military, political, and scientific organizations recognized the role that scientists, including oceanographers, could play in maintaining American interests. The National Research Council made the point explicitly when it created a new agency, the Pacific Science Board, in 1946.

> It has become widely evident that the prosecution of fundamental research in the Pacific area is a matter of vital importance to our national defense. Added to this are the new obligations that we have assumed as Trustees for the Japanese mandated islands. It may truly be said that the developments leading to the Pacific

> Science Conference and the establishment of the Board, are largely an outgrowth of World War II in the Pacific.43

The board laid out an ambitious program whereby scientists and social scientists would collect information about the peoples, languages, and socio-economic conditions throughout the southwestern Pacific. Oceanographers, it was hoped, would investigate currents, waves, ocean bottoms, and the interrelations of sea and atmosphere. The U.S. Geological Survey, which had established a military geology branch during the war, sent scientists throughout the Trust Territory to gather information on minerals and other economic resources.44 The navy had similar needs. Many military leaders remained convinced that the United States had been unprepared for the war in the Pacific, and did not want to be in that position again. The ongoing need to ensure that the United States was well prepared for detecting and hiding submarines required continued research on underwater acoustics, bottom sediments, and bathymetry. For protection of beaches and harbors against underwater guided missiles, atomic bombs, or other threats, the navy needed scientists to gather data and develop predictive models that would provide military forces with a strategic advantage in virtually any situation. The demands of amphibious warfare required ongoing research and testing to ensure ready access to beaches, islands, and atolls. Those who spoke for the navy's bureaus frequently emphasized technological needs, yet many also noted the role that science and technology would serve in securing America's expanding economic, political, and military objectives in that region.45

Scientists, however, had mixed feelings about an ongoing relationship. Many understood the navy's interest, but few wanted to remain involved in war related work.

Oceanographers made that point at a January 1945 meeting on demobilization. Iselin, Sverdrup, Fleming, and Spitzer agreed that after the war the oceanographic unit in the Hydrographic Office should be expanded and become the center for naval oceanography. Yet they also stated:

> the civilian oceanographic laboratories should serve mainly as consultants to the Hydrographic Office in problems of pure science and should undertake work under Navy sponsorship only where experience in broad fundamental research is required to aid in obtaining results of ultimate practical significance. It should be their function to explore such problems as are more or less remote from the immediate routine of the Navy laboratories and to maintain a pool of qualified personnel which can be drawn on as necessary by the Navy.

Eager to return to research, and wary about issues of secrecy, ability to publish, and the increased costs and bureaucracy that would accompany military support, those scientists sought to distance themselves from navy operations.46

Yet Sverdrup, Iselin, and their colleagues also realized that oceanography could not do without the navy. The navy could provide greater financial support than any other entity; it also maintained control of vessels and instruments that were necessary for deep sea research. Oceanographers, in short, needed the navy as much as the navy needed oceanographers. It also became increasingly clear that although scientific and naval views on the purposes of oceanographic research differed, there was agreement on what constituted the main topics of investigation. In March 1945 Sverdrup, responding to a request from the Research Board for National Security, drew up a program on postwar studies of the oceanography of surface layers. While Sverdrup identified many topics of interest to military and national security interests, his effort was not comprehensive. Given Sverdrup's limited security clearance, any program at Scripps could not include work in underwater acoustics. But neither was his document unique; other similar and more extensive listings became common and represented a growing consensus between civilians and naval leaders on postwar oceanography. What had emerged from discussions held throughout late 1944 and 1945 was a commitment to the idea that almost all fields of oceanographic research had potential navy applications. Studies of ocean bottoms, surface layers, coastlines, and almost any topic other than biological oceanography were, at once, both intellectually meaningful to oceanographers and operationally useful to the navy.47 Iselin, Sverdrup, and others played a major role in the dialogue that resulted in such an understanding, but it was Revelle, who remained in the Bureau of Ships after the war, who took the lead in implementing it.

He did so first on Operation Crossroads, albeit with mixed results. In the fall of 1945, when Revelle and his colleague Norman J. Holter proposed that oceanography be included in that project, they emphasized navy priorities. The Crossroads Baker test was designed to assess the physical effects of the atomic bomb on ships, and Revelle and Holter pointed out how wave measurement studies and instruments developed by the Bureau of Ships during the war could contribute to that objective. It was only after their proposal was approved that Revelle suggested that the project include work on physical oceanography, biology, geology, and fisheries. He created an oceanographic section that included scientists from numerous civilian and military organizations, but within the context of a military mission their researches were "a corollary" to a more important purpose: determining the physical effects of the bomb on the waters, organisms, and geological features of Bikini Atoll. Revelle had hoped that U. S. Geological Survey scientists, using seismic refraction equipment employed in geophysical prospecting, could obtain data "on the controversial Darwin-Dana-Davis theory that coral atolls are built up from gradually submerging volcanoes." However, the Naval Ordnance Laboratory planned to take seismic profiles using depth charges, a technique that would enable the agency to test its low frequency receivers. That effort took priority, and the Geological Survey cancelled its plans for seismological work. USGS scientists participated in Crossroads, but their role was to assess the explosion's effects on atoll erosion, changes in bottom topography, and radioactive residue in bottom sediments. At Bikini technological and operational objectives took priority over scientific research, a point echoed by Walter Munk who lamented that "no one here . . . is interested in applying physical principles to the interpretation of data."48

Revelle, aware of the shortcomings of Crossroads, remained eager to promote scientific research under navy auspices. In 1946 he moved from the Bureau of Ships to the new Office of Naval Research (ONR) where he worked to promote that agenda on two fronts. By the time Revelle joined ONR, Robert Conrad and his colleagues had already designed contracts that allowed for generous funding of civilian research. As the head of the ONR Geophysics Branch, Revelle was instrumental in awarding contracts to institutions for research in oceanography and meteorology. He also had responsibility for ONR sponsorship of geographic exploration, and in 1947 he proposed a follow-up expedition to Bikini Atoll.49 In contrast to Crossroads, the Bikini Scientific Resurvey gave scientists a say about which vessels and instruments were necessary for their work. The resurvey included a science advisory board. Most important, the expedition gave scientists a role in designing the research projects. Whereas Crossroads provided little opportunity for study of coral reef formation, the resurvey devoted considerable resources to that problem. The geologists, Harry S. Ladd, Joshua I. Tracey, and Kenneth O. Emery, did more than supervise drilling operations on Bikini Island. Their field studies included dozens of reef traversals as well as analyses of the composition, slope, and movement of virtually all features of the reef, islands, lagoon, and nearby guyots. Marine studies included soundings, dredgings, bottom samplings and seismic refraction tests. That work relied on the latest equipment: echo sounders, bottom scanning sonar, underwater cameras, aerial photography and radar. Other scientists on the resurvey examined circulation systems and waves, the organic productivity of the reef, and the geothermal features of the atoll. In contrast to the secrecy that had enveloped the work done on Operation Crossroads, Revelle and Ladd arranged for the Geological Survey to publish the results of the resurvey.50

But the resurvey was not a strictly scientific expedition. It was a naval undertaking, and Revelle had also defined it in those terms. His proposal to the Joint Chiefs of Staff said nothing about fundamental research; it called for scientific studies of the long term effects of the Crossroads underwater bomb blast, recovery of instruments from sunken vessels, and collection of additional data for harbor defense against atomic attack. Studies of the atoll were equally germane to military needs. Shallow and deep water soundings not only elucidated the relationship between atolls and underwater volcanoes, they provided means for determining the locations and operations of new deep submergence submarines. Seismic refraction studies yielded information about subsurface geology and the underwater structure of atolls; they also tested underwater sound equipment, employed explosives as countermeasures against mines, and enhanced sound transmission studies for possible detection of underwater guided missiles or atomic explosions. Analyses of the sediments, gradients, and slopes of the reef and atoll were crucial for understanding "trafficability" and ensuring effective landing operations.51

Beyond technological and operational applications, the studies undertaken at Bikini Atoll would contribute to the military's long term objectives. As Revelle stated in 1947, there were

> two main reasons why we conduct expeditions today. One for scientific purposes, to discover new principles which control our environment and new natural resources, and two, for the purposes of waging war, In some cases these two purposes are entirely inseparable. It has become apparent that the society which knows the most about its environment and how to turn it to account, is going to be the more likely to win the next war.52

For the purpose of fighting and winning any future wars, the military needed to obtain extensive knowledge about the environments in which such wars would be waged, be it on land, in the sea, or under the sea. That knowledge was important for developing predictive models for waging war anytime, anywhere. It was also important for control. In addition to beachheads, islands and atolls, underwater formations and underwater sound channels were vital territorial resources that needed to be controlled. Oceanography, as a field science, contributed to that objective. In the case of the Bikini Scientific Resurvey, and much of postwar oceanography, scientific, military, and geopolitical purposes were inseparable.

Conclusion

A number of interpretations have been proposed to define the postwar relationship between the navy and oceanography. To Revelle and other scientists that participated, the Bikini Resurvey constituted a significant statement. Excited by Hess's wartime discoveries, they maintained that the expedition represented a commitment to fundamental research supported by a generous government patron. Weir has suggested that oceanographers in the postwar period effectively engaged in "piggybacking": adding scientific investigations onto military projects. Weart has claimed that oceanographers "painted their projects blue," pretending to do military work only as a means for gaining support for their science.53

This paper offers a different interpretation: that scientists willingly did military work and received funding for their scientific investigations. In contrast to the suggestion that scientists were able to chart their own path and disguise their intentions, this paper argues that they embedded or incorporated their interests within a military framework. In early 1945, when Fleming, Iselin, Sverdrup, and Spitzer laid out a program for postwar oceanography, they understood that the navy considered their work indispensable and identified ways in which their research could contribute to the military's technological and operational objectives. That proposal was a means of legitimizing their own interests, but those scientists also understood and accepted the idea that oceanographers would have to do military work. Iselin understood that obligation; so too did Revelle. As oceanographer and naval officer, he not only participated in the effort to design the postwar program; he served as the broker responsible for convincing the navy and scientists that military support of research would benefit both communities. The consensus achieved could be defined as a symbiotic relationship, but is perhaps better understood as a form of embedding. Recognizing that navy concerns were paramount, scientists sought to carve out a niche for their interests, but in a manner that would also serve military objectives.54

The dual role that scientists played is evident in the postwar activities that took place at Bikini. The resurvey was a navy sponsored expedition that enabled oceanographers to conduct research on questions that they deemed important. Military patronage may even have enhanced the scientific work done at Bikini. Operating under navy auspices, scientists had access to the latest and best equipment. The navy's multiple needs and demands, from underwater acoustics to bottom topography, required that expeditions include scientists from many fields. The opportunities for oceanographers to work with physicists, geophysicists, and engineers in isolated, labor intensive situations fostered interaction that may have contributed to new discoveries and interpretations. But scientists also served military needs. Oceanographers and geophysicists took part in Crossroads, even though it was a technical assessment of weapon performance that provided few opportunities for research. The multiple traversals done by Emery and Tracey on the resurvey had little to do with the study of coral reef formation. Rather they provided detailed information on how to access, cross, and establish beachheads on reefs. Harry Ladd complained that using loran to establish ship positions was difficult and "of limited usefulness," but it served the navy's interest in testing submarine detection equipment.55 Scientists touted the opportunity to conduct research investigations at Bikin, but their work accrued to the military's advantage by providing assessments of weapons and conditions in which they would be used, thereby contributing to the effort to understand and control the warfighting environment.

The social configuration between the two communities also supports this interpretation. It wa not a relationship between equals. As the dominant patron, the navy had a powerful say in what kind of scientific work was done, by whom, and with what equipment. Postwar expeditions took place in navy vessels under the supervision of navy personnel. With military sponsorship came an elaborate security system. Only scientists with security clearance could take part in navy sponsored projects. On expeditions all incoming and outgoing information, including information related to scientific work, required clearance. So too did publication of any findings, and much of the oceanographic work was, and remains, classified.56 Nor did the navy underwrite investigations in all fields. Some oceanographers continued research on plankton, marine organisms, and marine microbiology, but rarely with navy support. Prior to the war, it was geologists, not oceanographers, who studied the problem of coral reef formation. After 1945 the subject became interesting to Revelle and others because of its connection to geophysics and deep sea research, areas of considerable importance to the navy. In the postwar period oceanographers received support to pursue important research questions, but only on the navy's terms and only when such research contributed to the navy's objectives.

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ABBREVIATIONS TO FOOTNOTES

BS	Bureau of Ships
CNO	Chief of Naval Operations
DCNO	Deputy Chief of Naval Operations
DTRA	Defense Threat Reduction Agency
HO	Hydrographic Office
JMC	Joint Chiefs of Staff Meteorology Committee
NACP	National Archives, College Park, Maryland
NADC	National Archives, Washington, D.C.
NDRC	National Defense Research Committee
NRSL	Navy Radio and Sound Laboratory
OSRD	Office of Scientific Research and Development
RG	National Archives Record Group
RR	Roger Revelle Papers

SIO	Scripps Institution of Oceanography
SIOA	Scripps Institution of Oceanography Archives
SIOD	Scripps Institution of Oceanography, Office of Director
SIOSF	Scripps Institution of Oceanography Subject Files
UC	University of California
UCDWR	University of California Division of War Research
USGS	U.S. Geological Survey
WHOI	Woods Hole Oceanographic Institution

FOOTNOTES

1. Roger Revelle, "Foreword," K. O. Emery, J. I. Tracey, Jr., and H.S. Ladd, "Geology of Bikini and nearby atolls," USGS Survey Professional Paper, 260-A (1954), iii-vii.

2. Navy Press Summary No. 12, July 19, 1947, RG 374, DTRA, entry 47B, box 158, folder Outgoing Dispatches, NACP. Charles Darwin, The structure and distribution of coral reefs (London, 1842).

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4. Michael Aaron Dennis, "A change of state: The political cultures of technical practice at the MIT Instrument Laboratory and the Johns Hopkins Applied Physics Laboratory, 1930-1945" (Ph.D. diss., Johns Hopkins University, 1991); Paul Forman, "Into quantum electronics: The maser as 'gadget' of Cold-War America," Paul Forman and J. M Sanchez-Ron, eds., National military establishments and the advancement of science and technology (Dordrecht, 1996), 261-326; Bruce Hevly, "The tools of science:

Radio, rockets, and the science of naval warfare," Forman and Sanchez-Ron, National military establishments, 215-232; Chandra Mukerji, A fragile power: Scientists and the state (Princeton, 1989).

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(Boston, 1931); Thomas Wayland Vaughan, "The oceanographic point of view," Contributions to marine biology: Lectures and symposia given at the Hopkins Marine Station (Stanford, 1930), 40-56. Roger Revelle to Harald U. Sverdrup, October 26, 1936, RR, MC 6, Correspondence Series 1935-June 1936, box 1, folder 53, SIOA.

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13. H. W. Menard, The ocean of truth: A personal history of global tectonics (Princeton, 1986), 30-37.

14. Athelstan F. Spilhaus, " A bathythermograph," Journal of marine research, 1 (1937-1938), 95-100.

15. Columbus O'Donnell Iselin to John T. Tate, August 19, 1941, RG 227, NDRC, entry 78, box 39, folder Navy Conference September 5, 1941; "Woods Hole Oceanographic Institution work, October 1, 1940-November 31, 1941," RG 227, NDRC, entry 78, box 53, folder WHOI General. Ewing commented on that unique relationship in a letter to Iselin, April 10, 1942, RG 227, NDRC, entry 80, box 121, folder WHOI III L1 though L73.

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17. Weir, "Ocean in common," 323-334. Columbus O'Donnell Iselin to John T. Tate, October 1, 1941, RG 227, NDRC, entry 77, box 4, folder 01.90 prediction of sound ranges.

18. Naval Research Advisory Committee to the Technical Aide, Secretary of the Navy, January 28, 1941, RG 19, BS General Correspondence 1940-45, S 68 (underwater sound), box 1201, folder S68 #1, NACP.

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28. Iselin, Application of oceanography (ref. 11), 9-12; Eckart, "Fundamental studies" (ref. 22), 135-137. UCDWR, Maxmimum echo ranges: Their prediction and use (January 1944), RG 227, OSRD, entry 29, box 680, folder UC. On pro-submarine

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32. Edwin H. Colpitts to Gaylord P. Harnwell, June 27, 1944, RG 227, NDRC, entry 79, box 6, folder Harnwell. Rawson Bennett to Harald U. Sverdrup, May 9, 1944, RG 37, HO Security Classified General Correspondence, entry 49, box 31, folder A10-1/S68 428232. Revelle went to the Pacific theatre in July 1945 to oversee the use of bottom sediment charts and submarine supplements: T. A. Solberg to H. T. Orville, July

2, 1945, RG 38, DCNO (Air) Flight Division, Aerology Division, General Correspondence 1919-1945, box 3, folder H1 -(1), #1.

33. John T. Tate to Vannevar Bush, February 20, 1942, RG 227, NDRC, entry 77, box 8, folder 03.00. NRSL, "Report of survey of San Francisco harbor to determine locality of proposed locations for harbor defense installations," January 23, 1943; NRSL, "Survey of Puget Sound area: Report on the suitability of possible herald locations Strait of Juan de Fuca and Admiralty Inlet, State of Washington," February 5, 1943, RG 19, BS General Correspondence 1940-1945, box 1216, folder S68(4). On objections: ref. 21.

34. Guillermo Medina to W, B, McKean, February 1, 1944, RG 37, HO Security Classified General Correspondence, entry 49, box 23, folder 407972-408670; Hydrographer to Chief of Naval Operations, July 1, 1944, RG 37, entry 49, box 64, folder A9-1/EN-22, 476706. For equipment needed to invade Majuro and Kwajalein atolls: RG 37, entry 49, box 61, folder QH 588/H1-18, 471686.

35. H. H. Styfried to Captain Slayton, Aprl 25, 1944, RG 37, HO Security Classified General Correspondence, entry 49, box 62, folder A9-4/AG 84, 472511; and Commanding Officer U.S.S. Hydrographer, July 3, 1944, entry 49, box 63, folder A9-4/AG 84, 475846. H. H. Hess, " Drowned ancient islands of the Pacific basin," American journal of science, 244 (1946), 772-791. On expanded intelligence information gathering: port summaries for Calcutta, December 8, 1942, and Karachi, May 29, 1944: RG 37, entry 49, box 38, folder 442632.

36. Sverdrup's activities at UCDWR are referred to in the monthly work reports of the Oceanographic Division of UCDWR for July-October 1941, RG 227, OSRD, entry 29, box 672, folder UC. He also had a hand in at least two additional reports: "Accuracy

of echo ranges from bt observations," December 11, 1941, RG 227, OSRD, entry 29, box 672, folder UC; and "Report of the probable effects of sound rays on varying depth of sound projectors," December 18, 1941, RG 227, OSRD, entry 29, box 675, folder UC. Sverdrup's loss of security clearance is in: John T. Tate to Gaylord P. Harnwell, April 9, 1942, RG 227, NDRC, entry 79, box 15, folder H through June 1942. That loss stemmed from an FBI background check on Sverdrup: Federal Bureau of Investigation, File on Harald U. Sverdrup, FBI HQ 125-8951.

37. Roger Revelle to Edwin H. Colpitts, October 2, 1943, RG 37, HO Security Classified General Correspondence, entry 49, box 30, folder A10-1/S68, 428232; Roger Revelle to Edwin H. Colpitts, October 2, 1943, and Roger Revelle to Director Scripps Institution of Oceanography, October 2, 1943, HO Security Classified General Correspondence, entry 49, box 31, folder 1, A10-1/S68 428232. Also Roger Revelle to UCDWR, November 25, 1944, RG 227, NDRC, entry 77, box 6, folder 01.93 submarine supplements.

38. Harald U. Sverdrup to Robert Gordon Sproul, June 15, 1942, SIO Office of Director (Sverdrup), box 1, Correspondence January -June 1942. A "Method for forecasting of swell," was prepared in November 1942 by Seiwell's unit: RG 38, DCNO (Air), box 3, folder H1-(1) #2. On the oceanography subcommittee: JMC meeting December 8, 1942, RG 218, Joint Chiefs of Staff, Central Decimal File, 1942-1945, JMC Meetings, box 206, folder November 3, 1942, NACP. On Revelle's activities: January 7, 1943, RG 298, box 62, folder Oceanogaphic Data Volume I; January 27, 1943, January 28, 1943, April 29, 1943, and May 13, 1943, RG 218, JMC meetings, box 209, folder December 3, 1942 Subcommittees. On navy authority over oceanography: Vice Chief of

Naval Operations to Hydrographer, June 9, 1943, RG 38, DCNO (Air), box 3, folder H1-(1) #1. On adopting Sverdrup-Munk method: Hydrographer to Commander of the 8th Fleet, Ocober 7, 1943, RG 37, HO Security Classified General Correspondence, entry 49, box 16, folder H1 (383545) #2. JANIS reports, including chapters on oceanography, are in RG 319, Army Chief of Staff Reports and Messages, 1918-1951, NACP. Also see: Charles C. Bates and John F. Fuller, America's Weather Warriors 1814-1985 (Texas A&M, 1986), 48-102.

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Records of observations, 1 (1944),161-248. On WHOI: Susan Schlee, On almost any wind: The saga of the oceanographic research vessel 'Atlantis' (Ithaca, 1978), 13-107.

42. "Minutes of the meeting held in the Hydrographic Office," October 19, 1945, SIOSF, "U. S. Navy Hydrographic Office 1945-46," box 26, folder 25. Commander Amphibious Forces to Commander in Chief, U.S. Fleet, August 20, 1945, RG 38, Commander in Chief Confidential Correspondence 1945, box 1805, folder H1-(3) #1. E. W. Mills to Hydrographer December 11, 1945, RG 38, DCNO (AIr), box 3, folder H1 (1) #!. From late 1943 until the end of the war, Furer took part in numerous discussions on postwar research, including Charles E. Wilson's Committee on Post War Research and what eventually became the Research Board for National Security: RG 298, box 52, includes three large folders on postwar research.

43. The quote is from First annual report, Pacific Science Board (Washington, National Research Council), 6.

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