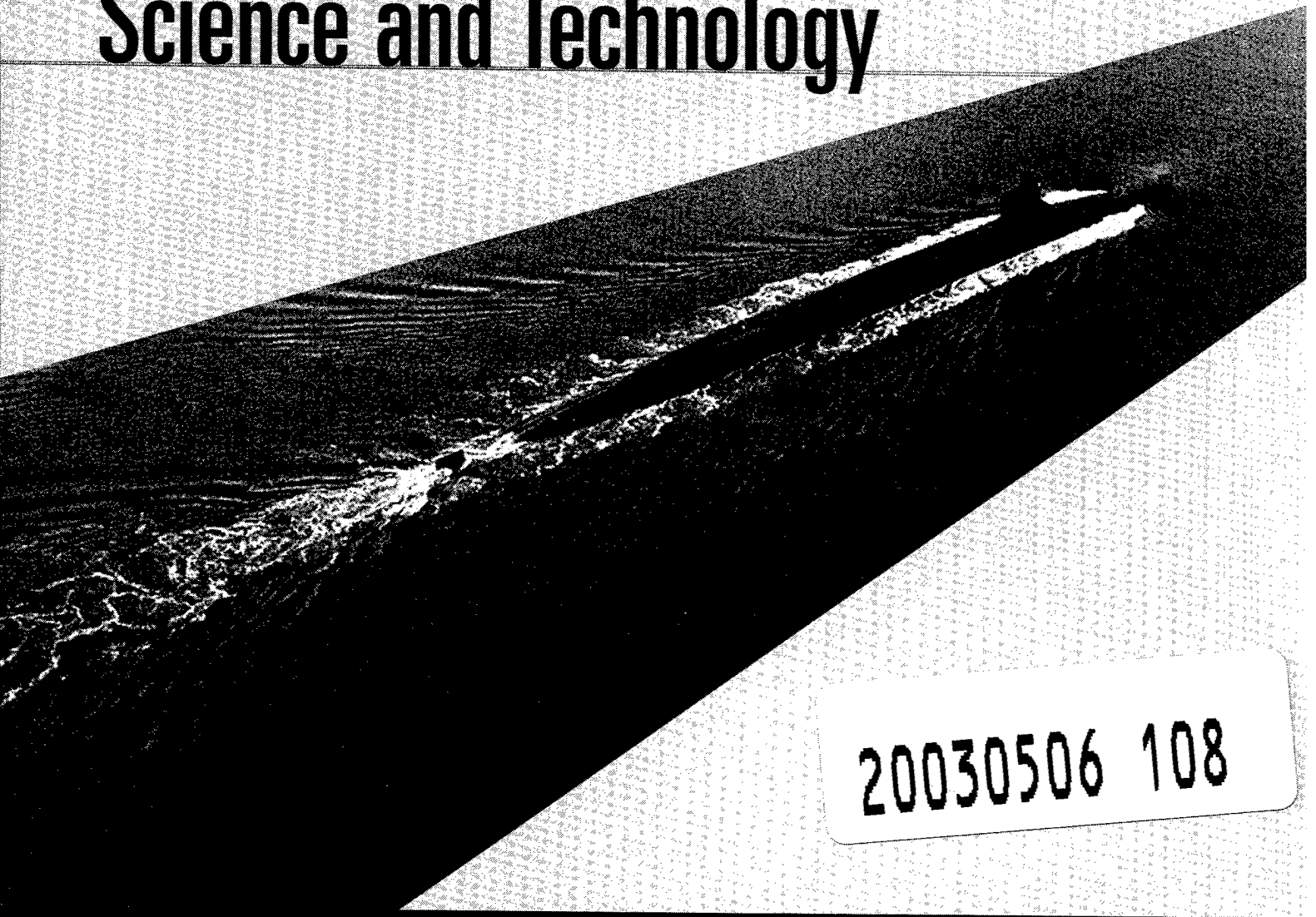


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An Assessment of Naval Hydromechanics Science and Technology



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An Assessment of Naval Hydromechanics Science and Technology

Committee for Naval Hydromechanics Science and Technology
Naval Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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Preface

The Department of the Navy maintains a vigorous science and technology (S&T) research program in those areas that are critically important to ensuring U.S. naval superiority in the maritime environment. A number of these areas depend largely on sustained Navy Department investments for their health, strength, and growth. One such area is naval hydromechanics, that is, the study of the hydrodynamic and hydroacoustic performance of Navy ships, submarines, underwater vehicles, and weapons. A fundamental understanding of naval hydromechanics provides direct benefits to naval warfighting capabilities through improvements in the speed, maneuverability, and stealth of naval platforms and weapons. This level of understanding requires the ability to predict complex phenomena, including surface and internal wave wakes, turbulent flows around ships and control surfaces, the performance of propulsors, sea-surface interactions, and associated hydroacoustics. This ability, in turn, stems from the knowledge gained from traditional experiments in towing tanks, from at-sea evaluations, and, increasingly, from computational fluid dynamics.

Historically, the Office of Naval Research (ONR) has promoted the world leadership of the United States in naval hydromechanics by sponsoring a research program focused on long-term S&T problems of interest to the Department of the Navy, by maintaining a pipeline of new scientists and engineers, and by developing products that ensure naval superiority. At the request of ONR, the National Research Council, under the auspices of the Naval Studies Board, conducted an assessment of S&T research in the area of naval hydromechanics. The Committee for Naval Hydromechanics Science and Technology was appointed to carry out the following tasks during this study: assess the Navy's research effort in the area of hydromechanics, identify non-Navy-sponsored research and development efforts that might facilitate progress in the area, and provide recommendations on how the scope of the Navy's research program should be focused to meet future objectives. Attention was given to research efforts in the commercial sector as well as international research efforts, and to the potential of cooperative efforts.

The committee assessed the existing program in the following areas: maturity of and challenges in key technology areas (including cost drivers); interaction with related technology areas; program funding and funding trends; scope of naval responsibility; scope, degree, and stability of non-Navy activities in key technology areas; performer base (academia, government, industry, foreign); infrastructure (leadership in the area); knowledge-base pipeline (graduate, postdoctoral, and career delineation); facilities and equipment (ships, test tanks, and the like); and integration with and/or transition to programs in a higher budget category. Two key questions for the assessment were the following: (1) What technology developments that are not being addressed, or that are being addressed inadequately, are needed to meet the Navy's long-term objectives? and (2) To what extent do these technology developments depend on Navy-sponsored R&D?

A timely report was requested for use in the Navy Department's planning for its S&T investment, which includes identifying critical research areas (i.e., National Naval Needs) for Department of the Navy sponsorship. In a memorandum to all personnel at the ONR, Fred E. Saalfeld, Executive Director and Technical Director, ONR, wrote as follows:¹

The purpose of a National Naval Program [now called a National Naval Need] is to allow ONR to meet its responsibilities to maintain the health of identified Navy-unique S&T areas in order that:

- A robust U.S. research capability to work on long-term S&T problems of interest to the DoN [Department of the Navy] is sustained;
- An adequate pipeline of new scientists and engineers in disciplines of unique Navy importance is maintained; and
- ONR can continue to provide the S&T products necessary to ensure future superiority in integrated naval warfare.

The assumption of national responsibility for the support of a research area requires the long-term commitment of a significant level of investment. It can also have non-military benefits and applications unforeseen at the onset of scientific research. To assist in this effort, ONR should continue its efforts to encourage and exploit investment in these areas by other research sponsors. It is therefore imperative that U.S. superiority in these areas be maintained, even at the sacrifice of niche opportunities.

The committee met in Washington, D.C., for briefings by the Navy and by others in the hydromechanics community on September 14 and 15, 1999, and on October 20 and 21, 1999, holding parallel sessions on classified and international research. In addition to these group meetings, individual committee members gathered additional information to help the committee form its collective judgment. This included information from ONR research programs and funding, from Navy Department hydromechanics test and research facilities and development efforts, from research funded by the Air Force Office of Scientific Research and the National Aeronautics and Space Administration, and from professional societies. A subcommittee also attended a briefing entitled "Fast Ships," which was presented by Paul E. Dimotakis at the JASON² Fall Meeting on November 19, 1999. On December 8 and 9, 1999, the full committee met for the third and last time to finalize the report. The resulting report represents the committee's consensus view on the issues posed in the charge.

¹Memorandum from Fred E. Saalfeld to ONR, November 19, 1998.

²The JASONs are a self-nominating academic society that conducts technical studies for the Department of Defense (meets in July, August, September, and October and produces a report in November).

Acknowledgment of Reviewers

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The contents of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. The committee wishes to thank the following individuals for their participation in the review of this report:

Alan J. Acosta, California Institute of Technology (emeritus),
Christopher E. Brennen, California Institute of Technology,
RADM Millard S. Firebaugh, USN (retired), Electric Boat,
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Robert C. Spindel, Applied Physics Laboratory, University of Washington,
Marshall P. Tulin, University of California at Santa Barbara (emeritus), and
Ronald W. Yeung, University of California at Berkeley.

Although the individuals listed above provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the NRC.

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Executive Summary

In this report, naval hydromechanics is defined as the study of both the hydrodynamic and hydro-acoustic performance of naval ships, submarines, underwater vehicles, and weapons. For brevity, the report often uses just the term "hydromechanics," but the reader should clearly understand that this includes hydroacoustics, which is of unique importance to the Navy for reasons that are explained herein. During the Cold War, the Department of the Navy benefited greatly from a steady flow of new ideas in naval hydromechanics. The new ideas generated from research sponsored by the Office of Naval Research (ONR) and research in the Department of the Navy research centers were incorporated into platforms and weapons to improve their speed, maneuverability, and stealth. Continued advances in naval systems can be expected from more recent, current, and future research in hydromechanics. These advances should enable faster, more agile, and stealthier platforms and weapons suitable for operation in both the littorals and the deep ocean.

Because ship and submarine hydromechanics are so specialized, they are not priority areas for other agencies, nor are they the focus of industrial research efforts. Thus the Department of the Navy must provide the necessary support if it wishes to ensure that U.S. naval forces always benefit from superior technology. Accordingly, the committee recommends as follows:

- *To enable the Department of the Navy to maintain superiority in naval hydromechanics and to allow the necessary resources to be devoted to this aim, ONR should designate naval hydromechanics as a National Naval Need.*¹

The committee is concerned that ONR support for research in ship and submarine hydromechanics and, in turn, the output of new ideas and technology have declined over the past decade. The current

¹As stated by Fred E. Saalfeld to the Office of Naval Research (ONR), National Naval Programs (now called National Naval Needs) are those science and technology areas that are uniquely important to the naval forces and whose health depends on ONR investment. See the preface for additional discussion.

system relies partially on funding made available from major acquisition programs, which in turn produces dramatic variations in the funding for naval research. This arrangement adversely impacts ONR's ability to maintain a research program focused on the long-term S&T problems of interest to the Department of the Navy—guaranteeing a pipeline of new scientists and engineers and developing products that ensure naval superiority. The work associated with variable funding from major acquisition programs is naturally oriented to the needs of the acquisition programs and therefore tends to be shorter-term and less adventuresome in scope than is required to produce revolutionary changes in technology. Today's 6.1 research will support new ship concepts a decade from now. The committee therefore sees the need for a stable base of funding outside of the acquisition programs for ONR, specifically for work in naval hydromechanics at the 6.1 level. Based on its judgment, the committee recommends as follows:

- *ONR should implement the following changes in research policy as it relates to hydromechanics:*

1. Funding for 6.1 should be less focused on immediate needs and more focused on broad, long-term research on fundamental problems in naval hydromechanics such as linear and nonlinear wave dynamics, including wave breaking, air entrainment effects, and air/sea interactions; all aspects of cavitating and supercavitating flows, including inception, noise, and damage; drag reduction and other aspects of flow control; surface and submerged wakes; hydrodynamic sources of noise; internal wave generation and propagation; and vortex dynamics and turbulence unique to naval surface and subsurface vehicle/sea interaction.

2. The 6.1 resource base should be stable and should be protected from the larger funding fluctuations associated with major acquisition programs.

3. In the 6.1 area, ONR should promote a culture of bottom-up research, which can bring novel developments and lead to solutions for unanticipated problems that may arise in the future.

The committee is concerned that the Department of the Navy does not have an integrated, long-term plan for science and technology (S&T) programs aimed at developing and exploiting new platform concepts for ships and submarines. It therefore recommends as follows:

- *ONR, in conjunction with the relevant Office of the Chief of Naval Operations and the Naval Sea Systems Command/Program Executive Office organizations, should formulate and maintain an integrated 6.2/6.3 plan for technology development and demonstration aimed at new platform concepts for ships and submarines and using the results of long-term basic research under ONR sponsorship. Key features of this plan should include (1) significant advances in a 15-year time frame, (2) clearly articulated goals in the related hydromechanics areas of signature reduction, drag reduction, propulsive efficiency, and seakeeping/maneuverability, and (3) the examination of concepts that could achieve these goals. Demonstrations necessary to ensure the validity of predicted performance should be described. The investment required and the resulting payoffs in terms of improvements in stealth, speed, cost, and payload capability should be assessed. The plan should guide 6.2/6.3 research and development efforts. The planning process should involve experts from the industry that engineers and builds naval systems; these experts must have long-term vision. The plan should also (1) require and accommodate innovative and competing approaches, (2) foster collaboration between the Department of the Navy, academia, industry, and, where appropriate, foreign organizations, (3) identify opportunities for areas of fundamental research, and (4) stimulate concepts for spin-off to commercial applications.*

- *Continuous channels of communication should be established between the research, design, and operations communities to ensure the effective use of research results and to inform researchers of specific problems as they arise. It is anticipated that improved communications at the Department of the Navy and between the department and the industrial and academic communities will lead to a stronger research program with significant future payoffs for the Department of the Navy.*

The committee expressed concern about various aspects of the Department of the Navy's research centers. There are numerous facilities and they are large, but they do not have the world-class instrumentation needed to do cutting-edge hydromechanics research. Few of the facilities appear to have been qualified to the careful level required for high-quality research. Some of the facilities appear to be idle more than one would expect in view of the research needed to match the imaginative developments that are occurring in commercial ships. If the Department of the Navy were to provide a financial incentive for commercial organizations to use these facilities, much as NASA does with its wind tunnels, a higher quality of facility and better support might become available to both military and commercial users of the facilities. Computational fluid dynamics (CFD) at the centers is expanding in importance and effort, yet world-class computing facilities are not available and some of those doing CFD work on naval problems are not in the mainstream of modern CFD developments. This concern is not limited to CFD researchers. Overall, while several of the researchers in the Department of the Navy's centers are highly regarded in the research community, that number is small compared with total staffing, and they are spread across a number of different facilities. The Department of the Navy hydromechanics research centers are a national asset and should be supported accordingly. Therefore, the committee recommends as follows:

- *The Department of the Navy should take the following steps to ensure that high-quality S&T is conducted at the hydromechanics research centers:*

1. *The Department of the Navy should consider retiring some of the less advanced facilities at the centers so that the rest can be improved and supported by better technical know-how and more manpower. Facilities that have shown no significant work or major instrumentation upgrades for a long time (say, 10 years) should be considered for decommissioning.*

2. *The Department of the Navy should aggressively pursue advanced measurement techniques (e.g., noninvasive, holographic, ultrasonic, and velocimetry techniques).*

3. *The maintenance and upgrade of hydromechanics facilities at the Department of the Navy centers should be funded from a separate source not linked to the S&T program.*

4. *The fundamental basis for experimental work at the Department of the Navy's centers should be strengthened. Experts from the different centers should be involved in intercenter scientific committees promoting the scrutiny and discussion of issues such as design and upgrade of facilities, qualification and documentation of the characteristics of an adequate facility, development and acquisition of new instrumentation and measurement techniques, physical interpretation of data, and evaluation of the scientific merit of the proposed experiments and the results obtained. Funding allocations should be based not only on the merit of proposed work but also on a track record of significant contributions from past work. The high quality of the Department of the Navy centers can be maintained by regular internal and external peer review and an emphasis on the refereed publication of research results.*

5. *A more active collaborative relationship between university and center researchers should be facilitated to take advantage of the strengths of both and to create a stronger overall research effort. Top-notch researchers from universities and other research institutions should be involved in research at*

the centers. The centers should use university researchers as active members of working teams in technical and scientific matters, design, facility upgrades and modifications, instrumentation design, and data presentation and interpretation of results. In addition, facilities and their use should be subjected to periodic evaluation by external experts.

6. *The quality of the research and technical management staffs should be improved over time by providing a more attractive research environment for the best and brightest university graduates.*

The committee is also concerned about the declining base of expertise and the lack of emphasis on naval hydromechanics in the research community that supports the Department of the Navy's needs. It therefore recommends as follows:

- *ONR should establish an institute for naval hydrodynamics (INH) subject to the following guidelines:*

1. *The INH should capture the best talents and the largest body of knowledge in hydromechanics from the United States and foreign countries. It should leverage existing funding and ensure a well-coordinated approach to research in hydromechanics.*

2. *The INH should be directed by a highly qualified scientific leader. The management style and philosophy should be in tune with the intellectual creativity expected of participants in the INH.*

3. *A small central facility should support the INH. This facility should be open to all INH participants.*

4. *The form of the center should be carefully determined. One attractive option would be a virtual center that uses distributed assets and extensive Internet communication. The virtual center would have a management committee and a small central supporting entity. The new NASA Astrobiology Institute organized by the NASA/Ames Research Center, the European Research Community on Flow, Turbulence, and Combustion, and the NASA Institute for Advanced Concepts are models for virtual centers. Virtual centers could draw upon researchers anywhere at any time. Although the idea is relatively new and relatively untested, it is very promising, and the committee recommends that it be given serious consideration. Alternatively, the center could be modeled after the jointly managed NASA/Stanford Center for Turbulence Research and the independently managed Institute for Computer Application Science and Engineering, at NASA/Langley.*

The committee believes that if the resources to support the initiatives recommended above can be found from new sources or budgetary rearrangements, the Department of the Navy will be in a good position to maintain its technical superiority in hydromechanics in the decades ahead.

Introduction

In this report, naval hydromechanics is defined as the study of the hydrodynamic and hydroacoustic performance of naval ships, submarines, underwater vehicles, and weapons. The importance, value, and contributions of naval hydromechanics science and technology (S&T) to the success of naval forces can best be understood from a historical perspective. The era most relevant to the purpose of this study extends from the formation of the Office of Naval Research (ONR) shortly after World War II to the present. During that period, the technical accomplishments of naval hydromechanics are epitomized by those of the David W. Taylor Model Basin (now the Naval Surface Warfare Center, Carderock Division (NSWCCD)). Some examples of its accomplishments, along with other examples from two white papers on naval hydromechanics written by Marshall P. Tulin¹ and Thomas T. Huang,² are described here.

- After World War II, basic hydromechanics research was conducted to support submarine construction and operation. A series of 24 body-of-revolution hulls (DTMB Series 58) were tested in a towing tank to determine their resistance, motion stability, depth and course-keeping control, and ocean surface effects at high speeds. An optimal axisymmetric hull shape had minimum resistance and a mild pressure gradient enabling the development of a hull boundary layer suitable for placing control surfaces upstream of a single-screw propeller. This basic research provided the Navy with a concept for a superior submarine that had reduced flow resistance, more effective control, and highly efficient propulsion. This submarine concept could improve not only the speed but also the stealth performance. A 20 percent gain in propulsion efficiency could be achieved by using the wake-adapted single-screw propeller instead of twin-screw propellers. The axisymmetric hull provided the minimum circumferential inflow variation to the propeller, which drastically reduced propeller-induced noise and cavitation.

¹Tulin, Marshall P. 1999. "Naval Hydrodynamics: Perspectives and Prospects." Santa Barbara, Calif.: Ocean Engineering Laboratory, University of California. September 14.

²Huang, Thomas T. 1999. "Contributions of Fundamental Hydromechanic Research to Advancing Fleet Technology." Crystal City, Va.: Newport News Shipbuilding and Drydock Company. December.

- The Navy's first research submarine, the USS *Albacore* (SS 569), was built to evaluate at sea the innovative ideas of control and propulsion that had been derived from the basic research program, and it provided firm support for these ideas. With this submarine, the Navy, the science and technology community, and the shipbuilding industry stepped outside the traditional technology box of the fleet submarine. The fundamental data obtained on a new hydrodynamic hull, control surfaces, and propulsion, along with the utility of low-carbon, high-yield-80 structural steel, became the foundation of U.S. submarine design and construction for the next half century. The development of the high-speed submarine hull form is a prime example of a technological breakthrough. It enabled a submerged submarine to travel well in excess of 30 knots. More importantly, when combined with the parallel development of nuclear propulsion, it resulted in the U.S. Navy's first truly high-speed submarine. The research foundation and technical expertise made possible by sustained investments in Navy S&T substantially enabled this revolutionary advance in naval warfare capability.

- Equally important to the continued superiority of U.S. submarines have been the sustained improvements in submarine stealth. The sudden increase in submarine speed and endurance produced an urgent need for quiet propulsion for stealth and for effective control for submarine safety. This drove the hydromechanics S&T community to continue to improve the stealth and hydromechanics performance of the submarine fleet. A long-term national S&T research program was implemented to solve the acoustic side effects of sustained submerged high speed and to meet the threat of the Soviet submarine fleet during the Cold War period. Fundamental and applied stealth and hydromechanics research was vigorously pursued in the Navy's laboratories and in universities, under the sponsorship of the ONR. Hydromechanics innovations ranging from advanced propeller designs to reduced hull acoustic radiation have enabled a large reduction in submarine signatures. As a result of a broad range of technological developments, U.S. attack and ballistic submarines have maintained an underwater acoustic advantage over the submarines of all other navies.

- The Small Waterplane Area Twin Hull (SWATH) ship concept was developed from the technology base and design methods established by sustained investments from Navy 6.1, 6.2, and 6.3. This concept permits greatly improved seakeeping and seaway performance, particularly in small and medium-sized ships. Innovative design configuration capabilities were also developed, including the unique steering system embodied on the TAGOS 19 and a number of semiactive and active control system concepts. SWATH technology has been applied commercially to a large (12,000-ton) passenger/cruise ship and to all-weather ferries and hydrographic and survey ships. At present, about 40 naval and commercial SWATH ships have been built worldwide.

- Surface ship hull form technology and design methods have been applied to recent classes of surface combatants, resulting in superior seakeeping, powering, and acoustic performance. This major performance advance is a direct result of years of investment in hull form technology R&D.

- Continued compilation of the variability of sea conditions and their statistics has improved the seakeeping design specification for surface combatants, and satellite ocean wave observations have provided timely guidance for ship operations. The basic understanding of ship response to the ocean waves associated with different sea states has improved the ability to design surface combatants with better seakeeping characteristics, less deck wetness, cost-effective shell plating and hull girders, and improved helicopter landing and takeoff operations.

- The sustained development and implementation of numerous innovations in the fleet have reduced energy consumption and operating costs for U.S. Navy ships. Innovations include new, environmentally acceptable, effective hull antifouling coatings; improved hull and propeller cleaning and maintenance programs; and stern modifications that permit fuel savings of 3 to 10 percent for several

classes of surface ships. All of these advances are supported or enabled by a sustained capability in hydromechanics research and design.

- In the late 1970s, the Navy needed to improve the target acquisition range of the Mk 48 torpedo. A limiting factor in the performance of the acoustic array was a basic hydrodynamic phenomenon, the noise caused by the transition from laminar to turbulent flow. The Naval Undersea Warfare Center (NUWC) developed the methodology to optimize array diameter, acoustic window thickness, transition location, and cavitation index and to resolve the key issue of window deformation under hydrodynamic loading. Experiments determined the location and intensity of the transition region, so that techniques to predict transition location could be validated. These advances in technology capabilities led to a substantial reduction in self-noise and a major improvement in torpedo performance.

- Hydrodynamic modeling based on theoretical and experimental research has played a critical role in the development and improvement of fleet weapons by providing estimates of forces and moments experienced by these vehicles during launch and maneuvers. Hydrodynamic force and moment predictions generated through this research were used as inputs to vehicle launch and trajectory simulations and throughout the development and design process. This process was instrumental in the development of Mk 46 and Mk 48 torpedo hardware and software and to a succession of advanced weapons such as the advanced capability and Mk 50 torpedoes.

- Basic research in hydromechanics and naval technical expertise have enabled advances in propulsor design through enhanced simulation and experimental methods that directly and indirectly reduced the noise signatures of Navy submarines, weapons, and tactical-scale vehicles. Substituting a single rotation propulsor for the traditional counterrotating propellers has meant indirect noise reduction due to machinery simplification while maintaining high efficiency and off-design performance. Using alternatives to traditional propulsor design reduces propulsor-radiated noise.

Trends and Emphasis

NAVAL NEEDS

The recent shift in naval warfare doctrine and strategy has caused the warship design community to rethink the relative importance of total ship system characteristics. In their policy papers "...From the Sea"¹ and "Forward...From the Sea,"² the Navy and the Marine Corps described a fundamental shift in focus from a global threat to regional challenges and opportunities. With this shift came a broadening of the Department of the Navy's mission, from one of mainly blue-water global operations to one of "... project[ing] power from the sea to influence events ashore in the littoral regions of the world across the operational spectrum of peace, crisis and war."³ Put in another way, "Our attention and efforts will continue to be focused on operating in and from the littorals."⁴

This shift in emphasis, in doctrine, in operating environment, and in focus places new demands on the performance and signatures of naval weapons and platforms. "Our ability to command the seas in areas where we anticipate future operations allows us to resize our naval forces and to concentrate more on capabilities required *in the complex operating environment of the 'littoral'* [italics added] or coastlines of the earth."⁵

While operating in the oceanographically and hydrodynamically complex and challenging littoral regions, and with an offensive focus toward the land, platforms such as submarines and surface ships are significantly more vulnerable to a wider variety of air, surface, and subsurface threats. These threats

¹O'Keefe, Sean (Secretary of the Navy), Admiral Frank B. Kelso II, USN (Chief of Naval Operations), and General C.E. Mundy, Jr., USMC (Commandant of the Marine Corps). 1992. "...From the Sea—Preparing the Naval Service for the 21st Century: A New Direction for the Naval Service." U.S. Department of the Navy, The Pentagon, Washington, D.C., September. Available online at <<http://www.chinfo.navy.mil/navpalib/policy/fromsea/fromsea.txt>>.

²U.S. Department of the Navy. 1997. "Forward...From the Sea—The Navy Operational Concept." The Pentagon, Washington, D.C., March. Available online at <<http://www.chinfo.navy.mil/navpalib/policy/fromsea/ffseanoc.html>>.

³U.S. Department of the Navy, 1997, "Forward...From the Sea," p. 1.

⁴U.S. Department of the Navy, 1997, "Forward...From the Sea," p. 2.

⁵O'Keefe et al., 1992, "...From the Sea," p. 2.

include shore-launched cruise missiles, diesel submarines, mines, missile boats, and torpedoes. Because of this, the Navy has placed new signature reduction requirements on new platforms such as DD 21 and the New Attack Submarine (Virginia class). These signature reduction design requirements are being set in all signature categories: acoustic, radar, magnetic, visual, and infrared. It is anticipated that all future platforms will be assigned signature reduction requirements more stringent than their predecessors.

The variety of threats and the budgetary restrictions suggest a rethinking of weapon characteristics as well. If capable sensors can be married to high-performance weapons, then ship characteristics can be matched to the resulting performance. For some scenarios, high-speed weapons launched from a stealthy platform can result in the most cost-effective total system. For the hydrodynamicist and hydroacoustician, the stringent future requirements for platform stealth and weapon speed will provide S&T challenges for the next decade.

RESEARCH AND DEVELOPMENT

The paradigm for engineering design and system development is changing. Throughout most of the twentieth century, the development of complex systems, including warships, was based on a limited amount of relatively simple analysis and a large amount of prototype testing. Over the past decade there has been a significant shift to much more analysis, computation, and physics-based simulation of different system alternatives prior to fabrication and physical testing. The prime enabler of this shift has been advances in computation technology. The benefits are shorter design time, reduced testing costs, and better products, as exemplified by the Boeing 777. This new approach to engineering design and system development will significantly alter the way that naval platforms and weapons are developed in the future.

There have also been changes in the nature of academic programs and research. Programs aimed at specific industries and systems, such as railroads, automobiles, electric power, and ships, have largely been phased out. The needs of those industries for engineers are now largely met by graduates of broader programs, such as mechanical engineering, chemical engineering, electrical engineering, and computer science, working together in multidisciplinary teams. The funding for university research has also undergone a shift that emphasizes multidisciplinary team research rather than focused, fundamental work by individual faculty. This has made it increasingly difficult for experts in fields of special interest to the Department of the Navy to maintain their more specialized research programs.

PROGRAM FUNDING AND FUNDING TRENDS

Table 2.1 and Figure 2.1 show naval hydromechanics funding from FY94 to FY99. Data provided by ONR show that both 6.1 and 6.2 funding levels in hydromechanics at ONR have been in overall decline since at least FY94. This decline probably extends further back in time and is consistent with the overall decline in government support for basic and applied engineering research. Except for FY99, no funding was allocated to 6.3 hydromechanics.

In constant FY99 dollars, category 6.1 core funding has declined by 47 percent since FY94, with a maximum reduction of 50 percent in FY98. Overall 6.1 funding approximately doubled from FY98 to FY99, but 86 percent of that growth came from one-year funds directed at short-term applications. The long-range core funding picture is hardly affected by this one-time infusion. Category 6.2 funds are 181 percent above their FY94 levels in constant FY99 dollars, after a low in FY96 of 35 percent below FY94 levels. However, about one-half of the growth in FY99 is a one-time infusion, similar to the 6.1 case.

TABLE 2.1 Naval Hydromechanics Funding from FY94 to FY99 in Then-Year Dollars (million dollars)

Department of the Navy S&T Funding Category	FY94	FY95	FY96	FY97	FY98	FY99
6.1	11.9	12.1	8.9	8.0	6.4	12.0
6.2	3.3	4.1	2.3	2.5	4.7	10.4
6.3	0	0	0	0	0	0.9
Other	8.0	4.0	4.5	4.1	3.1	1.6
Total	23.2	20.2	15.7	14.6	14.2	24.9

SOURCE: Compilation of data courtesy of the Office of Naval Research, Arlington, Va., December 1999.

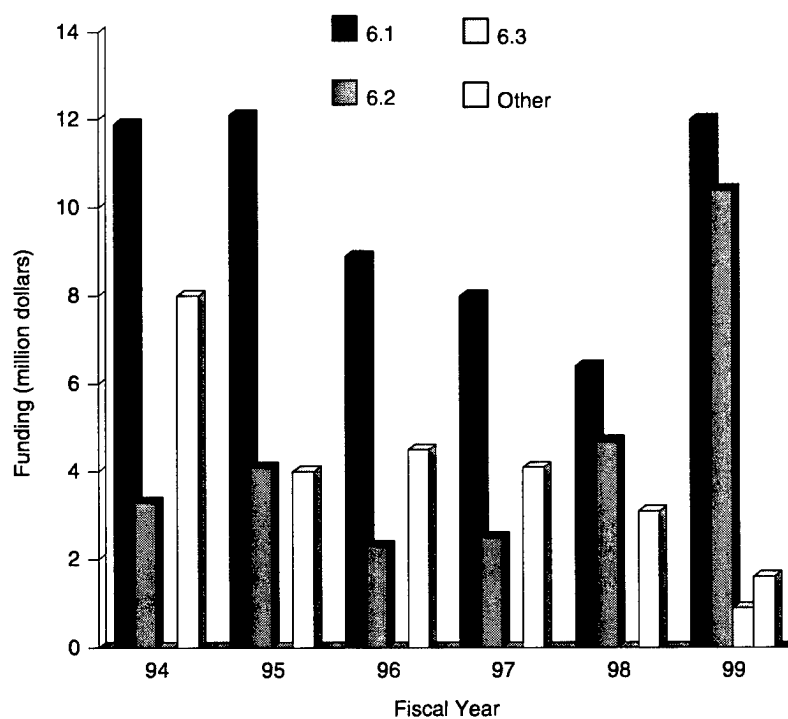


FIGURE 2.1 Naval hydromechanics funding from FY94 to FY99 in then-year dollars.

SOURCE: Compilation of data courtesy of the Office of Naval Research, Arlington, Va., December 1999.

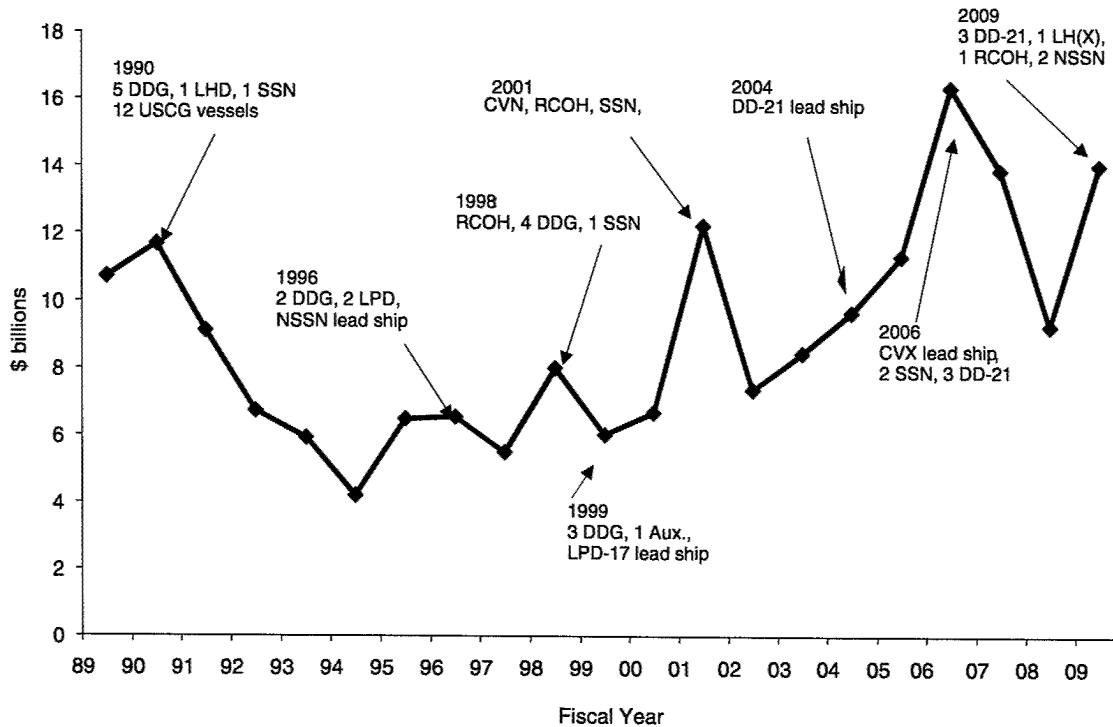


FIGURE 2.2 Ship construction, Navy budget, FY89 to FY09. Courtesy of Litton/Ingalls Shipbuilding, Inc., Pascagoula, Miss.

The category 6.2 situation is encouraging, but levels throughout this period have strained the Navy's ability to transition research to applications without resorting to the use of ship construction, Navy (SCN) funds to solve technology problems. This situation has been exacerbated by substantial declines in SCN budgets over the same period, as shown in Figure 2.2. Historically, technology development and technical solutions to fleet problems have been helped along with contributions from SCN funding. Not only is the lower SCN level a problem, but also as new ship classes become less frequent, an unstable profile results. This is not conducive to long-term research and technology goals, which benefit most from stable, well-planned technical efforts. Therefore, it is essential to have a critical mass of stable 6.1 and 6.2 funding.

Technology Issues

NAVAL NEEDS

Submarine Stealth

Submarine stealth depends critically on the level and character of its radiated noise. In the past, as in the foreseeable future, acoustics will be the principal component of a submarine's signature and could lead to detection and classification by adversaries' sonar systems at relatively long ranges. Nonacoustic components of submarine signatures are more localized in space and are important at closer ranges.

In the absence of cavitation, submarine acoustic signatures generally include narrowband tonals at blade rate frequencies and broadband noise. These tonals are caused by interactions of the propeller with spatially and temporally unsteady flow fields and structural vibrations induced by the resulting time-dependent forces. Before the current proliferation of towed array sonars, only ocean surveillance systems could capture low-frequency blade rate signals from long ranges, but ships and submarines could not take immediate advantage of this information. The larger acoustic apertures of modern towed arrays and progress in flow noise control have overcome this restriction. Even though this source of noise has received much attention, there are still no cost-effective ways to control it.

Recent data acquired on very quiet ships reveal noise sources caused by turbulent boundary layer flow that were hitherto hidden by other, more intense radiation mechanisms. Although direct radiation from boundary layers is very weak, a turbulent fluid boundary layer along an elastic solid boundary can generate significant noise levels. This elastic solid boundary may be the hull or trailing edges of lifting surfaces. The structural vibrations excited may have distinct resonance peaks in the radiated noise spectrum.

Cavitation gives rise to bubbles of vapor or gas that collapse and oscillate. As a generator of acoustic monopoles, cavitation is a very efficient radiator. It is unacceptable on submarines and highly undesirable on surface ships. Separated flows caused by submarine maneuvers lead to premature cavitation inception and to significant increases in radiated noise levels. Flow-induced sonar self-noise is also adversely affected.

Traditionally, full-scale cavitation inception was based on visual observations in water tunnels. This method, however, is not suitable for modern submarine propulsors as indicated by measurements made on the Large Scale Vehicle (LSV), a ¼-scale powered model of the SSN 21 submarine, at Lake Pend Oreille. Even with the relatively large size of the LSV, substantial scaling corrections for the cavitation inception number are necessary, because of a mismatch in Reynolds number. Differences in both scale and kinematic viscosity (due to temperature differences) contribute to the differences in Reynolds number. This is an important issue since laboratory research and field studies indicate that the inception index is strongly dependent on this parameter. Unfortunately, a precise, scientifically based scaling relationship is not available, making it problematic to predict the cavitation performance of some major weapon systems. A physics-based method for predicting cavitation inception would enable better and quicker design and reduced model and full-scale testing costs. Research in the Large Cavitation Channel in Memphis, Tennessee, should include fundamental work aimed at developing the needed physical models.

Although the discussion has so far concentrated on submarines, it applies generally to weapons silencing as well. In addition to hydrodynamics, the critical technologies are hydroacoustics and structural acoustics. Progress in all three technological areas is essential if future stealth requirements are to be met.

Surface Platforms

To prevent the detection and classification of surface platforms at long ranges, electromagnetic, hydrodynamic, and acoustic sources must be controlled. The hydrodynamic and thermal wakes of surface ships can be detected by a wide variety of electromagnetic sensors with frequencies ranging from visual to radar. Submarines generally detect and classify surface ships from the modulated cavitation noise generated by the propellers. In spite of very significant progress, propeller cavitation still begins at relatively moderate ship speeds. The level of radiated noise also adversely interferes with towed array beams directed toward the towing vessel. As in the case of submarines, maneuvers significantly degrade the acoustic signature of surface ships. The magnetic field of surface platforms extends to shorter ranges but is clearly critical for mine warfare.

To achieve the required stealth performance for surface ships, water tunnel and lake testing needs to be supplemented by model or full-scale measurements at sea to address specific stealth and signature problems. Air entrainment and bubbly flows cannot be adequately modeled in freshwater. It should be stressed that the tools are available to conduct almost laboratory-quality experiments in the field, and these could be conducted on a noninterference basis using naval vessels. The hydromechanics program also has to recognize that stealth and signature problems must be addressed in the context of the operational environment, and this is generally not well represented by towing tank wave fields. Surface ship (and submarine) signatures depend on the marine and atmospheric environments, and these must be measured or modeled for results to be useful.

Technology areas affecting surface ship stealth include hydrodynamics, hydroacoustics, and electromagnetics. Seakeeping and speed are other important considerations in ship design, and here hydromechanics is important: "The ability to develop hull forms capable of sustained operations at high speed in heavy seas would yield tremendous tactical benefits, and the peak performance of any crew is enhanced if the adverse effects of roll and pitch can be minimized."¹

¹Naval Studies Board, National Research Council. 1997. *Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st-Century Force*, Vol. 6, *Platforms*. Washington, D.C.: National Academy Press, p. 26.

Fast Ships

Transporting troops and equipment at high speed is an attractive goal, but current technical barriers limit the likelihood of achieving it. It therefore exemplifies the critical need for an innovative and aggressive S&T program in hydromechanics and marine propulsion.

An internal report by Colen G. Kennell of the Naval Surface Warfare Center, Carderock Division (NSWCCD) documents the results of an international meeting, the High-Speed Sealift Technology Workshop, hosted by the NSWCCD in October 1997. The report claims that "dramatic enhancements in sealift capabilities are possible if appropriate research and advanced development efforts are made." It cites seven technology areas where such efforts are necessary. Those that involve research in hydromechanics include advanced high-speed hull forms, drag reduction, hull/propulsor integration problems, and sea-induced loads. The report also indicates that very substantial financial resources will be necessary in other areas, such as fuel-efficient power generation and propulsion machinery as well as lightweight ship structures.

The high-speed ferry industry has demonstrated encouraging possibilities. Significant advances, however, will require the development and validation of analysis tools that can predict the performance of anticipated unconventional hull forms. Sea-induced loads, seakeeping, and propulsor/hull integration problems are likely to be significant and difficult to solve. They will require substantial research resources before analytical and numerical tools can be reliably used in design.

More recently, the JASONS conducted a study entitled "Fast Ships" that was sponsored by the ONR and the Defense Advanced Research Projects Agency (DARPA).² The study, conducted by a team of experts led by Paul Dimotakis of the California Institute of Technology, hypothesizes an extremely challenging future Navy mission and investigates ship concepts required to achieve the mission. The vehicle requirements are for a ship of about 10,000 tons with a payload of 1,000 to 2,000 tons and a range of 10,000 miles at a sustained ship speed of 75 to 100 knots. The ship should be of shallow draft and be able to transit the Suez Canal. One of the most stringent requirements is that the ship must be commercially viable.

The JASONS study team determined that the performance goal of 100 knots cannot be achieved with the best current technical capabilities, but a speed of 75 knots may be attainable if advances in drag reduction and flow control that seem possible can indeed be made. For this concept to become viable, an aggressive S&T effort in turbulent drag reduction technology would need to be successful. Such an effort is not in place today. Additionally, major advances would be required in high-speed seakeeping, in cavitation technology (e.g., supercavitation), and in propulsion (probably in electric propulsion concepts). "Fast Ships," in conjunction with the requirements for the nearer-term DD-21, points out the wide gap between the Navy's future hydromechanics needs, on the one hand, and the S&T programs in place to provide them, on the other.

²Dimotakis, P., P. Diamond, F. Dyson, R. Garwin, J. Goodman, M. Gregg, D. Hammer, and R. Lelevier. To be published. *Fast Ships: Hydrodynamics of Fast Ocean Transport*. Arlington, Va.: Office of Naval Research and Defense Advanced Research Projects Agency.

MISSING OR INADEQUATELY ADDRESSED HYDROMECHANICS SCIENCE AND TECHNOLOGY

Computational Simulation of Hydromechanics Phenomena

Computational simulations are making significant contributions to many important areas of naval hydromechanics. Computational fluid dynamics (CFD) in particular is proving to be extremely useful in submarine and ship design. Positive impacts are also being made in computational hydroacoustics (CHA) and computational wave dynamics (CWD), but there has been less emphasis and less progress in these areas than in CFD. Because there are no numerical means to simulate exact three-dimensional wave propagation, one cannot make a numerical wave tank (to put ships or other bodies in) in three dimensions. Surface waves undergo very complicated nonlinear interactions over moderate and long time scales that are extremely important in many ocean problems. Similarly, one cannot deal realistically with wave breaking and splashing and air entrainment numerically. With ONR support, large eddy simulation (LES) is becoming an important new tool for CHA. However, LES requires modeling of small-scale phenomena, and there are important Navy applications (e.g., air entrainment at the waterline) where LES could be useful but is limited by the small-scale modeling. Since CHA and CWD are largely of interest only to the Navy, the primary responsibility for the research needed to develop these models rests with the Navy. Further progress will depend on improved modeling of the complex physical phenomena, including those that are unique to hydromechanics, such as air entrainment, wave breaking, cavitation, and turbulent interactions with the free surface. There is also a great need for better numerical prediction methods for complex, nonlinear, three-dimensional wave fields and their interactions with ships.

The Navy centers all have ongoing efforts contributing to CFD, CHA, and CWD for Navy needs, and the ONR has sponsored substantial efforts at universities to develop CFD. These efforts have resulted in computational software and design tools that have contributed significantly to improved hull shapes and propulsor designs. Most of the software is focused on the solution of the unsteady Reynolds-averaged Navier-Stokes (URANS) equations, with modeling of the free-surface phenomena. However, URANS predictions are only as good as the turbulence models that they use. Current models do not do a very good job of predicting the location of separation induced by pressure gradients, do not handle the effects of frame rotation (as in propellers) properly, and do not handle the effects of microbubbles, polymers, and other small-scale elements that show great promise for flow control. LES is rapidly emerging as an alternative to URANS and is being actively explored by ONR.

There is a clear need for new and better small-scale modeling methods for use in large-scale CFD. These methods are likely to be best if they are soundly based on small-scale physics and associated asymptotic analysis of the effects of this physics at large computational scales. Unfortunately, asymptotic analysis has taken a back seat to computation with the rise in CFD. New efforts are therefore needed to use small-scale physics and asymptotic theory to generate better models for use in CFD, CHA, and CWD. The committee recognized that a substantial community in applied mathematics and theoretical physics is intensely involved in studying small-scale turbulence, which can benefit modeling for naval hydromechanics applications.

The direct numerical simulation of turbulent flow is one way to increase the knowledge base that is needed to develop improved models.

The committee believes that one role of the university principal investigator is to develop innovative numerical solutions that address generic difficulties impeding progress. It is not to specifically design CFD modules that can be added on to operational codes.

In addition, there is a need for carefully coordinated experiments and CFD simulations designed to improve understanding of the basic physical phenomena. Such an element is largely absent from the present program, where most of the CFD is directed to the development of design tools. On the experimental side, there is a need to perform full-scale trials to resolve some of the scaling issues. These trials can take advantage of the existing LSV program.

Scaling to High Reynolds Numbers

When a new submarine or surface ship is being designed, the required performance parameters that are predicted by analytical or numerical methods must be validated by scale model tests. The data acquired experimentally are intended to demonstrate that the ship's specifications will be met. The parameters that are affected by hydromechanics include powering, maneuvering and control, seakeeping, cavitation, and acoustic and nonacoustic stealth.

The capabilities of the available test facilities and the cost of manufacture restrict the size of models to a small fraction of the full-scale ship. Experimental data are therefore obtained at values of Reynolds, Froude, and cavitation numbers at least one of which is very different from that of the real vessel. Although the basic scaling laws are well known, their application, especially by extrapolation, is still largely empirical. For conventional designs, the predictions generally agree well with full-scale measurements. However, even in these cases there have been important exceptions where extrapolations from the model scale have failed, with potentially severe consequences.

The Department of the Navy Large Cavitation Channel in Memphis, Tennessee, has some very exciting possibilities for fundamental research. However, so far it has not been used very much for such research.

There is, accordingly, a need for new methods based on first principles for scaling experimental data from model systems to full-scale systems and for full-scale measurement programs to validate these results. The new methods will probably incorporate new abilities in flow prediction for full-scale systems of the type described above, but these predictive tools will themselves probably need to incorporate field data on full-scale systems. To solve these problems, the Department of the Navy could mount a concerted effort to develop the new scaling methods, determine the sort of field data needed, and develop the instrumentation to acquire these data in the field. This aspect of naval hydromechanics research is crucial for evaluating new concepts and will not be initiated or supported by any agencies other than the Department of the Navy.

Interface Physics, Chemistry, and Biology

In his white paper,³ Marshall P. Tulin provides a cogent overview of research issues that distinguish naval hydromechanics from other branches of fluid mechanics. In his summary, the major subdivisions of naval hydromechanics included free-surface hydrodynamics, cavitation, effects of stratification, resistance of ships, ship wakes, aeration, and remote sensing.

Ship waves, wind waves, and aeration are topics that are of continuing interest and importance. The understanding of the interaction of complex turbulent flows is far from complete. For example, a wake

³Tulin, Marshall P. 1999. "Naval Hydrodynamics: Perspectives and Prospects." Santa Barbara, Calif: Ocean Engineering Laboratory, University of California. September 14.

with a free surface requires a detailed understanding of the vortex interactions at the free surface. Free-surface turbulence has features that are quite different from the turbulence in fully submerged flow because of the complex vortical interactions at the free surface. Aeration due to ship waves, wave breaking, and boundary layer entrainment are also not well understood. A complete knowledge of the source of bubbles in the wake of a ship is far from within our grasp. All these topics are of crucial interest to the stealth problem of surface vessels and submerged vessels running at shallow depths.

Surfactants or contaminants on the free surface require special consideration, because they alter surface tension. Surface tension gradients have insidious effects such as the well-known Reynolds ridge phenomenon. Aeration physics and cavitation are also affected by the presence of surfactants.

The chemical makeup of the ocean, in conjunction with the thermal gradients, affects the stratification of the ocean, which in turn has a major impact on the formation and decay of ship and submarine wakes. Internal waves, driven by gravitational restoring forces on density gradients, have an impact on acoustic propagation and the operation of submarines in the ocean environment.

It is well known that viscous resistance is modified substantially by the presence of long-chain polymer additives (the Thoms effect). Naturally occurring algae, plankton, and other biomass can also affect ship resistance substantially. Outgassing from small animals in the sea and bubbles entrained by breaking at the surface account for the presence of cavitation nuclei at depth.⁴ Bubble formation and cavitation in seawater (rather than freshwater) have not been explored in depth. These physiochemical and biological effects are clearly of importance to the Department of the Navy and are not typically supported by the research programs of other agencies. Driving home this point, Tulin says that we have failed to learn enough about fundamental hydrodynamic phenomena related to surface effects and about how these phenomena relate to remote detection.

Two excellent sources of information on fluid dynamics research are *Research Trends in Fluid Dynamics*, published by the U.S. National Committee on Theoretical and Applied Mechanics, and *Annual Review of Fluid Mechanics*, published by Annual Reviews. These sources, however, mention very little about the physicobiochemical impact on naval hydromechanics. What is mentioned may be characterized as still unknown. An example is the chapter by A. Prosperetti,⁵ who says that "detailed mechanics [of cavitation damage] and possibly physicochemical aspects are not completely understood," and "the role of surface forces and contamination appears to be essential [to the processes of bubble splitting and coalescence]." Thirty-one volumes of the *Annual Review of Fluid Mechanics* have been published, yet it is difficult to find a specific reference to this topic.

In short, physicobiochemical effects on the hydromechanics of the ocean environment are highly relevant to the Department of the Navy. It is a topic that has received relatively little attention in the context of naval hydromechanics and is, moreover, clearly a topic that if not supported by the ONR will not be supported elsewhere.

⁴O'Hern, T.J., J. Katz, and A.J. Acosta. 1985. "Holographic Measurement of Cavitation Nuclei in the Sea." ASME Cavitation and Multiphase Flow Forum. Albuquerque, N.Mex.

⁵Prosperetti, A. 1996. "Multi-phase Flow, Cavitation, and Bubbles." *Research Trends in Fluid Dynamics*. J.L. Lumley, A. Acrivos, G.L. Leal, and S. Leibovich, eds. Woodbury, N.Y.: AIP Press.

Infrastructure

RESEARCHERS AND DEVELOPERS AND THE S&T KNOWLEDGE BASE

Introduction

Naval hydromechanics has its foundations in fluid mechanics, acoustics, applied mathematics, and physics. Students wishing to pursue careers in naval hydromechanics typically earn undergraduate degrees in naval architecture, ocean engineering, mechanical engineering, engineering science, applied mechanics, mathematics, or applied physics before pursuing graduate degrees in the same departments or specialized departments of ocean engineering or naval architecture.

The broader field of naval architecture or ocean engineering, like that of aeronautics, has three major component subfields: fluid mechanics (including propulsion and seakeeping), structures and materials, and stability and control. Students in undergraduate naval architecture programs would usually have a general training in all three subfields before specializing at the graduate level. The skills acquired in other engineering disciplines also find application in naval architecture. Given this broad base from which students may finally pursue careers in naval hydromechanics, it is very difficult to quantify how many students are actually capable of pursuing careers in naval hydromechanics.

It is also difficult to quantify the knowledge base at the other end, the performer base—that is, the number of experienced and accomplished researchers. Specific research problems in naval hydromechanics may attract the attention of researchers from a broad range of specialties in fluid mechanics and related areas. For example, surface ship signatures may depend on the detailed hydromechanics of the breaking bow wave, propeller cavitation, and the bubbly wake, or on other nonlinear problems in free-surface multiphase flows. Free-surface hydromechanics is a research topic of importance not just to naval hydrodynamicists but also to researchers in civil engineering, chemical engineering, physical oceanography, applied mathematics, and numerical analysis.

Fluid dynamics, or hydromechanics, has had a rich tradition of attracting some of the giants of science, mathematics, and engineering: Stokes, Kelvin, Laplace, Rayleigh, von Karman, Prandtl, G.I. Taylor, and Lighthill, to name a few. The applications are important, and the science and mathematics

are interesting and challenging. While specialization within the field has become more common, in the past its leaders distinguished themselves by applying their skills across the entire field. Lighthill, for example, made seminal contributions to aerodynamics, gas dynamics, acoustics, biofluidynamics, and meteorology.

The only supporter of hydromechanics research of any import is ONR. However, during the 1990s, ONR, and especially that part of ONR most relevant for naval hydromechanics, became more mission-oriented. That is, it became more concerned with solving specific problems over short time scales than with developing new knowledge that will support naval forces well into the twenty-first century. In view of federal budget constraints, this focus on the short term is understandable, but because of time constraints and limited horizons, short-term, mission-oriented research almost always becomes a synthesis of current knowledge rather than a generator of new knowledge. Individuals attracted to research are more excited by discovery than by synthesis, so the academic pipeline of younger researchers feeding into naval hydromechanics research is directly affected by the relative emphasis that ONR places on fundamentals.

In 1956 the Mechanics Division of the ONR used its resources to sponsor the first Symposium on Naval Hydrodynamics. The list of contributors to that first symposium attested to the significance of the field: Milne-Thomson, Lighthill, Stoker, Munk, Longuet-Higgins, Wehausen, Benjamin, Birkhoff, Strasberg, Batchelor, Gilbarg, Plesset, Lin, Klebanoff, and Corrsin. Barely a decade after World War II and well into the Cold War, the need to maintain naval superiority was never far from the minds of those scientists who could contribute to the field. But they were not scientists who made their reputations doing mission-oriented research—they were scientists who attacked problems having broad implications and applications, and they changed their field in the most fundamental ways. Having scientists and engineers of this stature making contributions to the Navy Department's needs in hydromechanics was ONR's goal in the 1950s and should again become its goal today.

Over the past 30 years there has been a substantial reduction in the number of programs in naval architecture, but this should not be interpreted as evidence that naval hydromechanics is a fully mature field. For example, although the equations describing hydromechanical flows are well established, they are nonlinear and can be solved analytically only for rather special flows or when linear approximations are adequate. However, important hydromechanics problems can be solved only by numerical methods (see "Computational Simulation of Hydromechanics Phenomena" in Chapter 3). Furthermore, because very different scales can be involved, modeling of the subgrid scale physics is often required, and this presents significant computational challenges. When wave breaking, air entrainment, cavitation, and turbulence are important, as they are in many naval hydromechanics problems, the modeling and computation are more difficult, and current capabilities are not adequate. Thus there are both needs and opportunities for research in naval hydromechanics. But because it is not a field in its infancy, it is more difficult to make rapid advances than it was 30 years ago, so research is even more essential to progress than it was in the past.

Distribution of Research Performers

Naval hydromechanics research is conducted in three types of institutions: academic, government, and private. The list of FY99 principal investigators in the hydromechanics programs of ONR 333, the Mechanics and Energy Conversion S&T Division, provides insights into the distribution of hydromechanics research across these institutions.

Nearly every university department of engineering, physics, or mathematics could be included as a potential performer of hydromechanics research. In the ONR tabulation, 63 of 101 projects were

affiliated with academic institutions, but of those, only 8 were in traditional naval architecture departments. Clearly, the bulk of ONR-sponsored hydromechanics research is being conducted at universities, but only a small portion of it is being done in departments of naval architecture.

The second category, government laboratories, accounts for 23 research projects in the ONR tabulation. The principal participant is the Naval Surface Warfare Center, Carderock Division with 18 projects. The other participants are the Naval Undersea Warfare Center (2), the Dahlgren Coastal System Station (1), the Naval Postgraduate School (1), and the Naval Sea Systems Command (1).

Private corporations and laboratories account for a total of 12 projects. Of these, Science Applications International Corporation, Inc. (SAIC), which has both East Coast (Annapolis, Maryland) and West Coast (La Jolla, California) branches with major hydromechanics capability, has three projects. Other private contractors with one project each include two aerospace companies (Lockheed Martin Astronautics and Lockheed Georgia Co.), one shipbuilder (Bath Iron Works in Maine), and other specialized firms (Dynaflow, Unamachines, Physical Optics, Northwest Research Associates, Pacific Marine & Supply, and Vibtech).

Finally, the ONR tabulation lists three projects in three overseas organizations: the Maritime Research Institute of the Netherlands, University College, London, and Ecole Centrale de Nantes, two of which are universities.

Another measure of naval hydromechanics research activity can be found in publications in scientific journals. Author location and source of funding were compiled for articles in two of the main U.S. publications devoted to hydromechanics research: the *Journal of Ship Research*, published by the Society of Naval Architects and Marine Engineers (SNAME), and the *Proceedings of the International Workshop on Water Waves and Floating Bodies*. Tables 4.1 and 4.2 list the total number of articles addressing naval hydromechanics issues, the number of articles by authors from U.S. laboratories and institutions, and the number of publications in which the work was sponsored in part or entirely by ONR, as indicated by the authors' acknowledgments.

It is apparent from these two tables that the number of U.S. researchers compared with non-U.S. researchers who had papers published in the two journals has declined dramatically since the 1960s and to a lesser extent within the last 10 years. This drop appears to be consistent with the reduced percentage of ONR acknowledgments, suggesting the importance of ONR funding for U.S. researchers in naval hydromechanics. If the United States is to maintain its naval superiority, it must ensure the vitality of the U.S. research community in naval hydromechanics by providing resources for longer-term fundamental research in the underlying disciplines (e.g. fluid mechanics, acoustics) and for the development of new concepts in naval hydromechanics. Support of longer-term basic research would expand the R&D personnel base by attracting established researchers working directly in naval hydromechanics.

Academic Pipeline (Graduate, Postdoctoral, and Career Delineation)

The issues that influence student enrollment and career choices are many and complex and certainly beyond the scope of a report such as this. However, some observations can be made that have a bearing on the attractiveness of naval architecture and naval hydromechanics as career choices. Engineering schools are currently dominated by departments of electrical and computer engineering. Undergraduate students are generally concerned with job opportunities and salaries, and those with degrees in these disciplines are in great demand, so naturally great numbers of students are attracted to these fields. Reports of U.S. industry being unable to find enough U.S. citizens to fill positions have made headlines as companies lobby the federal government to liberalize visa quotas for foreign engineers.

TABLE 4.1 Hydromechanics Articles Published in the *Journal of Ship Research*, 1959-1998

Year	Total ^a	U.S. ^b	% U.S.	ONR ^c	% ONR
1959	15	13	87	4	27
1960	12	11	92	4	33
1961	13	13	100	7	54
1962	14	14	100	8	80
1963	10	10	100	8	80
1964	15	10	67	6	40
1965	22	19	86	10	45
1966	16	13	81	7	44
1967	20	17	85	11	55
1968	18	15	83	10	56
1969	22	20	91	10	45
1989	20	10	50	6	30
1990	18	10	55	7	39
1991	24	12	50	5	21
1992	20	13	65	7	35
1993	20	11	55	8	40
1994	20	8	40	3	15
1995	15	5	33	3	20
1996	20	4	20	3	15
1997	15	7	46	5	33
1998	19	8	42	4	21

^aTotal number of articles in year (four issues) on naval hydromechanics subjects.^bArticles with lead author from U.S. institution.^cONR support acknowledged by authors.TABLE 4.2 Hydromechanics Articles Published in the *Proceedings of the International Workshop on Water Waves and Floating Bodies*, 1986-1999

Year ^a	Total ^b	U.S. ^c	% U.S.	ONR ^d	% ONR
1986*	37	17	46	1	30
1987	34	7	21	2	6
1988*	39	17	44	1	2
1989	53	19	36	8	15
1990	49	9	18	2	4
1991*	52	21	40	8	15
1992	54	10	19	1	2
1994	52	8	15	2	4
1995	58	13	22	1	2
1996	48	8	17	1	2
1997	52	8	15	2	4
1998	46	9	42	4	4
1999*	47	10	21	2	4

^aAsterisk denotes workshop held in the United States.^bTotal number of papers presented at workshop.^cPapers whose first author is affiliated with U.S. institution.^dNumber of papers acknowledging support from ONR, NRL, or Applied Hydrodynamics Research.

TABLE 4.3 Number of Students and Postdoctoral Fellows in Hydromechanics Supported by ONR in FY99

Program	Postdoctoral	Doctoral	Master's	Undergraduate	Total
Submarine hydromechanics	8	22	11	11	52
Surface ship hydromechanics	16	25	12	13	66
Total	24	47	23	24	118

SOURCE: Data provided by Office of Naval Research.

At the graduate level, similar concerns affect the student's choice of field, but they are often tempered by personal circumstances (e.g., marriage, family, earnings, and location preference), which may play a larger role in the career decisions of the potential researcher than they did in his undergraduate days. While unique circumstances may lead a student to pursue a research career in naval hydromechanics, the employment choices compared with those for the student of computer engineering are rather limited. While the computer engineering researcher has a vibrant U.S. private industry sector competing for talent, the shipbuilding industry in the United States maintains itself only in niche markets, one of which is shipbuilding for the Navy. The cutting edge of naval architecture in the United States, the place where excitement and innovation are to be found today, is in the design and construction of America's Cup boats, but this is not a large market. Thus, for all intents and purposes, it is only the universities, the government laboratories, and the builders of U.S. naval ships and weapons that can offer stable employment to those graduates who have strong interests in naval hydromechanics.

The number of graduate students trained in any field of science and engineering is directly proportional to the level of university research funding in the field. Table 4.3 shows the number of students and postdoctoral fellows engaged in hydromechanics research supported by ONR in FY99. Assuming a residence time of 5 or 6 years in an MS/PhD program and that all holders of master's degrees go on to win PhDs, this support would graduate 12 to 14 PhDs per year. If the MS students were terminal master's students, the number of graduating PhDs would drop to 8 to 10. An average of these estimates would give 10 to 12 PhDs per year, without accounting for attrition, which could reduce these numbers by 25 percent, say, to 8 to 9.

Table 4.4 shows the number of academic degrees at the bachelor's, master's, and PhD levels

TABLE 4.4 Number of Degrees Awarded in Selected Fields

	Bachelor's (1996) ^a	Master's (1996) ^b	PhD (1996) ^a	PhD (1998) ^b
Marine sciences	NA	NA	NA	18
Naval architecture and marine engineering	329	29	7	NA
Ocean engineering	167	112	30	29
Oceanography	185	142	105	94

^aU.S. Department of Education. 1999. *Digest of Education Statistics 1998*.

^bNational Science Foundation. 1999. *Survey of Earned Doctorates 1998*.

awarded in recent years in naval architecture and related fields. These are not large numbers, especially the number of PhDs.

In comparing the data of Tables 4.3 and 4.4 and in drawing conclusions from them, it might be noted that none of the students who were supported by ONR in FY99 were registered in naval architecture departments, so none will get degrees in naval architecture.

At the undergraduate level there are substantial degree programs in naval architecture and marine engineering at the University of Michigan at Ann Arbor, the University of New Orleans, and the Webb Institute of Naval Architecture. The ocean engineering BS program at the Massachusetts Institute of Technology serves as a feed for the MS program in naval architecture. Table 4.4 shows that the total number of bachelor's degrees awarded in naval architecture and marine engineering was 329 in 1996. Since the U.S. shipbuilding industry currently hires 250 to 300 naval architects per year, it can be concluded that there is an approximate balance between supply and demand.¹

In the past 20 or 30 years, the most significant graduate programs in naval hydromechanics were at the University of California at Berkeley, the University of Michigan at Ann Arbor, and the Massachusetts Institute of Technology. In the past 2 or 3 years, large reductions occurred at two of these programs: the Department of Naval Architecture and Offshore Engineering at the University of California at Berkeley was discontinued and several faculty at the Massachusetts Institute of Technology retired.

In-depth expertise in the field of naval hydromechanics in the United States is maintained by an aging cadre of engineers and scientists. At steady state, with professional careers spanning 35 to 40 years, the 7 to 9 PhDs graduating each year in the United States (see Tables 4.3 and 4.4) would be enough to sustain a population of approximately 250 to 360 professional researchers in naval architecture. The performer base in naval hydromechanics would be even smaller than that were it not for the ability of naval hydromechanics to attract researchers who are trained in broader disciplines. Given the fact that the performer base is biased toward its older members, it is likely that this rate of PhD production will not match the rate of retirements in the short term, leading to a decline in the number of researchers.

Universities that have significant programs in hydroacoustics are Boston University and Pennsylvania State University. Universities with faculty members in hydroacoustics-related subjects include Notre Dame, the University of Minnesota, Florida Atlantic University, the University of Maryland, Virginia Polytechnic Institute, and the University of Houston. Some senior researchers at NSWCCD participate in graduate programs by supervising graduate research at Notre Dame and Florida Atlantic University. Most PhD candidates supervised in this way have joined NSWCCD, and they have competence in structural acoustics and hydroacoustics. NSWCCD's Signatures Directorate generally hires mechanical and electrical engineers. In the past, arrangements were made with Catholic University to teach courses in acoustics, signal processing, and fluid mechanics to new engineers. Selected staff members have also been encouraged to pursue graduate degrees during sabbaticals. While there is no large infrastructure in hydroacoustics at U.S. universities, laboratories like NSWCCD still manage to meet their personnel needs by means of the kind described above.

Through its enlightened funding of fundamental science and engineering, ONR has built up a loyalty among the principal investigators in academia, and they stand ready and prepared to respond

¹Coincidentally, Japan, formerly the leading shipbuilding country, currently graduates approximately 300 students with bachelor's degrees in naval architecture each year. Anecdotal evidence suggests that not all of them can find jobs in the shipbuilding industry.

when ONR or the Department of the Navy needs advice or technical support on more immediate problems. This is an important resource that is difficult to quantify, but it is likely that any further erosion of ONR's tradition of being concerned with fundamental research will lead to a decline in numbers in that community and in their ability to respond.

Research Culture in the Department of the Navy Centers

The committee has some concern about the research environment at the Department of the Navy centers, which appear to be focused on the performance testing of prototype systems rather than on research that could lead to fundamentally different systems. Testing is important to the Department of the Navy, but so is research, and the strategies for managing testing laboratories and research laboratories are quite different. There may not be enough freedom for Department of the Navy researchers to explore and develop new ideas, and this opportunity needs to be cultivated by the management of these centers.

Several researchers in the Department of the Navy centers are highly regarded by their peers in the research community, but their number is relatively small compared with the total number of research staff at these centers, and they are spread across a number of different facilities. Each of the centers is operated independently, and the experts at the various centers do not seem to have much interaction. Most of the centers' work is published in conference proceedings as opposed to refereed journals and thus escapes critical peer review.

In contrast, NASA research centers encourage publication in refereed journals. There is a policy to subject all NASA reports to internal peer review before they are submitted. Nothing like this appears to take place in the Department of the Navy centers, even making allowance for the department's work with classified information. If publication was encouraged, perhaps the Navy Department laboratories would attract more of the best and brightest university graduates, and the technical level of their contributions would be higher.

RESEARCH FACILITIES FOR NAVAL HYDROMECHANICS TECHNOLOGY

The discussion in this part of the report addresses issues related to national asset hydromechanics experimental facilities and active academic test facilities, non-U.S. facilities, and problems associated with the facilities.

National Asset Hydromechanics Test Facilities and Active Academic Test Facilities

Experiments are now performed at two Department of the Navy centers using the facilities listed in Box 4.1 and at the academic facilities listed in Box 4.2. More details are given in Appendix A. In the United States there is one comprehensive Navy Department laboratory, NSWCCD, with towing tank and water tunnel facilities capable of testing the large-scale models needed in many types of naval studies. Several universities have towing tanks and water tunnels, but except for the tunnels at Pennsylvania State University and the medium-sized towing tank at the University of Michigan, the facilities are small and devoted primarily to teaching and graduate student research. Two large facilities, the Davidson Laboratory and Hydronautics, Inc., have ceased or nearly ceased operation in naval hydromechanics. The latter, based in Fulton, Maryland, was the largest private firm devoted almost solely to naval hydromechanics S&T. Although the company closed a number of years ago, the tank and tunnel facilities still exist, and two small engineering firms continue to use them at a low level of activity,

BOX 4.1 Department of the Navy Centers and Facilities**Naval Surface Warfare Center,
Carderock Division**

Circulating water channel
 Large cavitation channel
 Towing basins (shallow water, deep water, and high-speed)
 Maneuvering and seakeeping basin
 Rotating arm facility
 Anechoic flow facility
 140 ft basin
 Research vessel *Athena*
 Variable-pressure cavitation tunnels (12, 24, and 36 in.)
 8 x 10 ft subsonic wind tunnel

**Naval Undersea Warfare Center,
Newport**

Acoustic wind tunnel
 Langley seawater tow tank
 Research water tunnel
 Research tow tank
 Quiet water tunnel

primarily for commercial work. There are two wave tank facilities, one in Texas and one in southern California, focusing primarily on the needs of the offshore oil industry. Not included in Box 4.1 or Box 4.2 but worthy of mention as an important U.S. asset is the Hydronautics Towing Tank and High Speed Channel, the only commercial tank approved by the Maritime Administration for resistance measurements of subsidized ships.

Non-U.S. Facilities

In Europe, there are a number of large, well-staffed, well-equipped laboratories. Notable installations, comparable in importance and competence to NSWCCD, are the Maritime Research Institute of the Netherlands (MARIN), the Hamburg ship model basin, the Danish Model Basin in Copenhagen, the

BOX 4.2 Academic Hydromechanics Research Facilities

University of Michigan towing tank
 University of New Orleans towing tank
 U.S. Naval Academy towing tank
 Offshore Technology Research Center at Texas A&M University
 University of Minnesota water tunnel
 California Institute of Technology water tunnel
 Massachusetts Institute of Technology water tunnel
 University of Iowa towing tank
 Applied Research Laboratory, Pennsylvania State University

Swedish Model Basin in Gothenburg (SSPA), and the Norwegian Laboratory (MARINTEK). Most of these laboratories are subsidized by their national governments. All began as ship-testing laboratories devoted principally to the commercial shipbuilding industry, and all have broadened their operations to accommodate the needs of the offshore oil industry. One large European facility, the British National Maritime Institute, at Feltham, was shut down a few years ago, with the relatively new, large-scale model testing tanks being demolished and the land converted to other uses.

In Asia there are a greater number of privately operated facilities as well as some government laboratories. In the latter category are the Ministry of Transportation Laboratory at Mitaka, Japan, and the Korea Research Institute of Ships and Ocean Engineering at Taejon, South Korea. A number of the shipbuilders in Japan, including Mitsubishi Heavy Industries, Ishikawajima-Harima, and Mitsui Zosen Nippon Kokan Kiokai, and in Korea, including the Hyundai Maritime Research Institute in Ulsan and the Daeduk R&D Center operated by Samsung Heavy Industries, operate their own research laboratories, some with towing tanks and tunnels as large as those at NSWCCD.

Discussion of Problems

Maintenance and Utilization

The successful utilization of a facility depends heavily on its quality and condition, which in turn is controlled by the repair and maintenance (R&M) program in place. In the United States, R&M is funded by organizational overhead funds or by a direct surcharge to the project using the facility. In either case, this translates to increased project costs to the sponsor. As a result, significant amounts of hydromechanics testing have gone overseas, particularly to European facilities, which are less expensive to the customer while providing quality data. As foreign facilities continue to attract U.S. businesses, the result is a technology drain to foreign organizations and less use of U.S. facilities, which decreases their efficiency. If the cost of hydromechanics testing in the United States could be reduced, the S&T program would benefit significantly and the use of U.S. facilities would increase. The Department of the Navy has a program called Major Range and Test Facility Base (MRTFB) that funds R&M for test facilities and test ranges. It currently funds mostly aircraft test ranges but is not limited to this use. If these hydromechanics test facilities (see Boxes 4.1 and 4.2) pass the MRTFB composite criteria, they should be funded by this budget item.

Instrumentation

In general, the instrumentation used in the Department of the Navy centers seems very basic, perhaps because it is used to gather global data (e.g., drag, moments) rather than to address flow physics (e.g., wave breaking, turbulence). At least some of the work at the centers could benefit from more advanced flow measurement techniques, such as particle imaging velocimetry, holography, and other modern, noninvasive optical techniques, and from modern data processing. In addition, new sensors with the MEMS techniques are now available for the measurement and control of fluid flows and are expected to play a role in hydrodynamics. Each of the centers should have an ongoing program of instrumentation modification, but no such programs were mentioned in the presentations to the committee.

Flow simulations, adjusted to meet laboratory-scale experiments, are not always accurate when extrapolated to full-scale ships and submarines (see "Scaling to High Reynolds Numbers" in Chapter 3). To improve predictive technology, one needs to better understand the physics, and getting the answer is difficult if one cannot measure relevant physical parameters. There is a need to identify which experi-

mental data, taken either in the laboratory or the field, would provide the answers, and then to develop new instrumentation to obtain those data.

RESEARCH IN THE COMMERCIAL SHIPBUILDING SECTOR

Throughout World War II and the Cold War, the shipbuilding industry was responsible for rapid, high-quality, and high-volume ship production, but it did not participate much in hydromechanics research and development. Industry performed very efficiently during that period in critical design development and ship construction using technology developed earlier by the government.

Program- and platform-specific research performed in recent years at U.S. shipyards building warships has increased in both scope and quantity. This is due to mergers, the application of submarine technology, and the Acquisition Reform initiative, which has resulted in funded industry becoming involved in future programs much earlier. This research, however, has been oriented toward platform-specific solutions for a given program, which tend toward nearer-term solutions, not long-term basic and applied research focused on advancing technology.

Design authority essentially remained with the Navy until the mid-1990s, when acquisition reform initiatives led to the creation of industry-government teams that competed with one another during the ship design process. Thus there is some research being done in parallel with the design, but it is obviously platform-specific and heavily constrained by the design schedule. Most private shipyards have some hydromechanics research under way in their own independent research and development (IR&D) programs and/or in funded R&D by Navy Department laboratories. Much of this research is focused on hull form development using computational fluid dynamics tools and signature reduction. This research is platform-specific and will not necessarily advance hydrodynamics S&T. If it does not enhance the company's competitive position, no funding will be expended on any research. ONR appears to have recognized this, because its rather substantial effort in CFD appears to be at least partly intended to provide the industry with more advanced design tools.

The mergers taking place the past few years have meant that all large U.S. warships are produced by only three corporations (Litton, Newport News, and General Dynamics). The mergers have created a much larger critical mass of engineering talent within these three corporations at a time when a reduction of total ownership costs, best value, innovation, and cost-as-an-independent-variable studies, rather than lowest price, are being used by the government as an important criterion for selecting the winner in competitions. The total number of people in the engineering departments of the General Dynamics shipbuilding "family" (Electric Boat, Bath Iron Works, and National Steel Shipbuilding Company) exceeds 8,000; at Litton it exceeds 2,000; and at Newport News it exceeds 5,000. Of these 15,000 individuals, some 3,000 are degreed engineers, and there is an attrition rate of about 10 percent. This technical talent is partially funded by corporate IR&D budgets, which have become larger in recent years, supplemented by a larger amount of government-funded R&D. This funding is based on past industry activity on government contracts and anticipates the similar involvement of industry in future programs. Increasingly, the three shipyards are contracting with Navy Department laboratories, universities, and private firms to participate in the early stages of shipbuilding programs.

Technologies that were once being developed exclusively for future nuclear submarine programs, such as stealth, propulsion, survivability and new materials technologies, are being directly applied to new surface ship programs, such as DD 21, in order to meet specification requirements and respond to the need for increased innovation. This has caused shipbuilders to increase their research in these areas. Research for the commercial sector is usually performed in the same industrial or academic institutions

that perform Department of the Navy-supported research. No shipbuilder in the United States has a laboratory and/or testing tank in which any hydromechanics research is performed.

Commercial marine hydromechanics research aimed at the commercial shipbuilding and operating market is almost nonexistent in the United States. This has been the case almost continuously for the past 50 years, and certainly since the cessation of commercial shipbuilding subsidies in the mid-1970s. Some funding for research was provided in the past by the U.S. Maritime Administration (MARAD). However, this resource was used essentially for demonstration projects, such as the nuclear merchant ship of 50 years ago, and, later, a commercial hydrofoil passenger ship. More recently, the Maritime Technology Program (Maritech) has received some funding. Maritech, originally managed by DARPA with the support of ONR and MARAD and now managed by the Department of the Navy, is targeted at the application of commercial practices to military shipbuilding. The only substantial hydromechanics project funded by MARAD was the MARAD Systematic Series of Full-Form Ship Models carried out at Hydronautics, Inc., the results of which were published in 1987. This was not fundamental research but, rather, design development intended to produce systematic resistance, propulsion, and maneuvering empirical data for hull forms similar to those of tankers and bulk cargo carriers.

Nominal research support is provided by the SNAME hydrodynamics panel, but again, limited funding allows for little more than seed money for approximately five projects per year. Often these small grants enable the principal investigator to develop a new idea in sufficient detail to allow submitting a more comprehensive proposal to other sources for funding. The U.S. ship operating and shipbuilding industry has been noted for its reluctance to support R&D applicable to the commercial industry, primarily because the market is small or nonexistent.

The offshore oil industry has seen greater input to R&D projects funded by private sources. Typically, the larger projects are funded jointly by a number of oil and offshore operating companies. While many of these projects involve elements of basic hydromechanics (e.g., the vortex-excited vibration of flexible marine riser pipes), most are development projects centered on large-scale concepts. In recent years, this has resulted in the development of several innovative deep-water oil production platform concepts, including the tension leg platform, the guyed tower, and the spar platform.

Owing to the paucity of private research and design expertise in commercial ship hydromechanics, new commercial ships for U.S. owners, whether built in the United States or abroad, almost always have their hull forms and propellers designed abroad, at facilities such as MARIN or SSPA. Examples are the recent container ship designs for Matson and American President Lines.

In conclusion, most of the research being performed by the commercial private shipbuilding sector is focused on solving program- or platform-specific, near-term problems for future U.S. Navy shipbuilding programs.

INTERNATIONAL RESEARCH IN HYDROMECHANICS

Researchers in naval hydromechanics have had frequent and long-standing contact with the international hydromechanics community through semi-open conferences arranged by the American Towing Tank Conference and the International Towing Tank Conference and through open international conferences on cavitation, acoustics, waves, and other phenomena, arranged by various national technical societies. In addition, there are cooperative round-robin tests to evaluate testing facilities, cavitation and propulsion tests, and numerous technical visits.

To gain a better perspective on the ONR program in naval hydromechanics and also on the general status of hydromechanics research in the United States in relation to work being done in the rest of the world, the committee sought the advice of two well-respected international experts, Odd M. Faltinsen of

the Marine Hydrodynamics Department at the Norwegian University of Science and Technology and Makoto Ohkusu of the Research Institute of Applied Mechanics at Kyushu University in Japan. Certainly, important research is also being undertaken in other countries, but the efforts in Norway and Japan are considered to be quite representative of efforts in other countries, which professors Faltinsen and Ohkusu are well aware of.

Research is still far short of being able to predict real flows over ships at sea, with unsteady motion, breaking waves, slamming, water passing over the deck, and other complex effects. An estimate in 1989 suggested that the solution of the Navier-Stokes equations for unsteady water waves would require a teraflops-class computer. Although advances in computer hardware and software have been much more rapid than was then anticipated, computers are still not powerful enough for such simulations. Furthermore, analysis, computational simulation, and experiments need to be interconnected in an effective research program.

The Norwegian research is directed toward high-speed surface vehicles, offshore platform technology, and flexible containers. This has led to an emphasis on hydroelastic problems, which require both hydromechanics and structural mechanics. There is also a strong concern with the safety of both surface ships (seakeeping) and offshore platforms. Another area of emphasis is the control of marine systems, which merges the disciplines of hydrodynamics and control theory. Applications include the control of high-speed surface ships, controlled operations of side-by-side ships, and the control of towed objects. Overall, it is fair to say that the Norwegian research program is oriented toward practical applications rather than fundamental phenomena.

Likewise, there is a difference in the attitude to research between the United States and the East (Japan, South Korea, and Taiwan). Where the United States emphasizes rational theory and understanding, the East emphasizes short-term results and practical applications. Thus, the West has produced most of the novel ideas and methods in ship hydrodynamics, but the East has been successful in applying them.

The direction and emphasis of U.S. and Japanese research in hydromechanics can be compared by surveying the research categories of published papers in the proceedings of the ONR *Symposium on Hydrodynamics* series and in the *Journal of the Japanese Society of Naval Architects* of Japan, which can be considered to be representative of the research in the two countries. Box 4.3 lists categories of research and Figure 4.1 shows the relative number of papers published in each journal in the different categories.

The two countries have roughly equivalent efforts in most of the first seven categories, which relate to basic ship hydrodynamics, although the U.S. effort on cavitation (category 5) is significantly larger. In categories 8 and 9, experimental techniques and bluff body hydrodynamics, which are more relevant to fundamental hydrodynamics, there is almost no Japanese research. On the other hand, U.S. activity in the more practical applications (categories 10 and up) is very much less than that of the Japanese. The overall conclusion is that U.S. research has a more fundamental orientation while Japanese research is more practical. In computational fluid dynamics, for example, the United States has a greater emphasis on turbulence modeling and validation, while the Japanese have advanced further in the prediction of transverse and maneuvering forces, including the simulation, for example, of the response to rudder motions.

In summary, there is a greater emphasis on near-term practical research in other countries. These observations are quite consistent with the different objectives of the shipbuilding industry in the United States and elsewhere. Other countries primarily build surface cargo and passenger ships and offshore platforms, and their research must emphasize issues such as safety, seakeeping, and a reduction of the resistance to motion. The U.S. effort is primarily in support of the needs of the Department of the Navy,

BOX 4.3 Research Categories

1. Computational fluid dynamics (CFD) of ship steady flow (including flow at drift angle)
2. Wave-body interaction
3. Propulsor
4. Resistance (non-CFD)
5. Cavitation
6. Wave hydrodynamics
7. Experimental techniques
8. Bluff body hydrodynamics
9. Turbulence and wake
10. Simulation of ship motion (maneuvering)
11. Fluid mechanics in the ship context
12. Seakeeping
13. Maneuverability
14. Reduction of frictional resistance
15. Special propulsion
16. Environmental and coastal hydrodynamics

SOURCE: M. Ohkusu, Research Institute of Applied Mechanics at Kyushu University, briefing to the committee October 20, 1999.

so there is more emphasis on submarines and issues related to stealth, such as hydroacoustics, wakes, and cavitation. It appears unrealistic to expect the rest of the world to pursue the kind of fundamental research that is needed to underpin the design of future generations of United States naval platforms.

**SCOPE, DEGREE, AND STABILITY OF NON-NAVY ACTIVITIES
IN KEY TECHNOLOGIES**

Historically, fluid mechanics research at ONR has enjoyed a productive partnership with other agencies and military services. The principal members of this partnership with ONR were the NASA Aeronautics Program (and its predecessor, the National Advisory Committee for Aeronautics (NACA)), the Air Force Office of Scientific Research, the National Science Foundation, and, to a lesser degree, the Army Research Office and the Department of Energy research and technology programs. In fact, the core of the early ONR technical experts in fluid dynamics came from the NACA Langley Research Center as well as from the David Taylor Model Basin (now the NSWCCD). This partnership, in collaboration with the academic community and the federal laboratories, produced much of the rapid progress in fundamental fluid mechanics research in the 1950s, 1960s, and 1970s.

The Defense Advanced Research Projects Agency has from time to time initiated high-risk and high-payoff advanced submarine technology programs with wide participation of industry. Currently it is supporting advanced sensors and payload development for future submarines. The DARPA programs are of short duration (average of 3 years) and are aimed at demonstrating the feasibility of revolutionary technology concepts. They provide few contributions to long-term research stability or to the fundamental knowledge base.

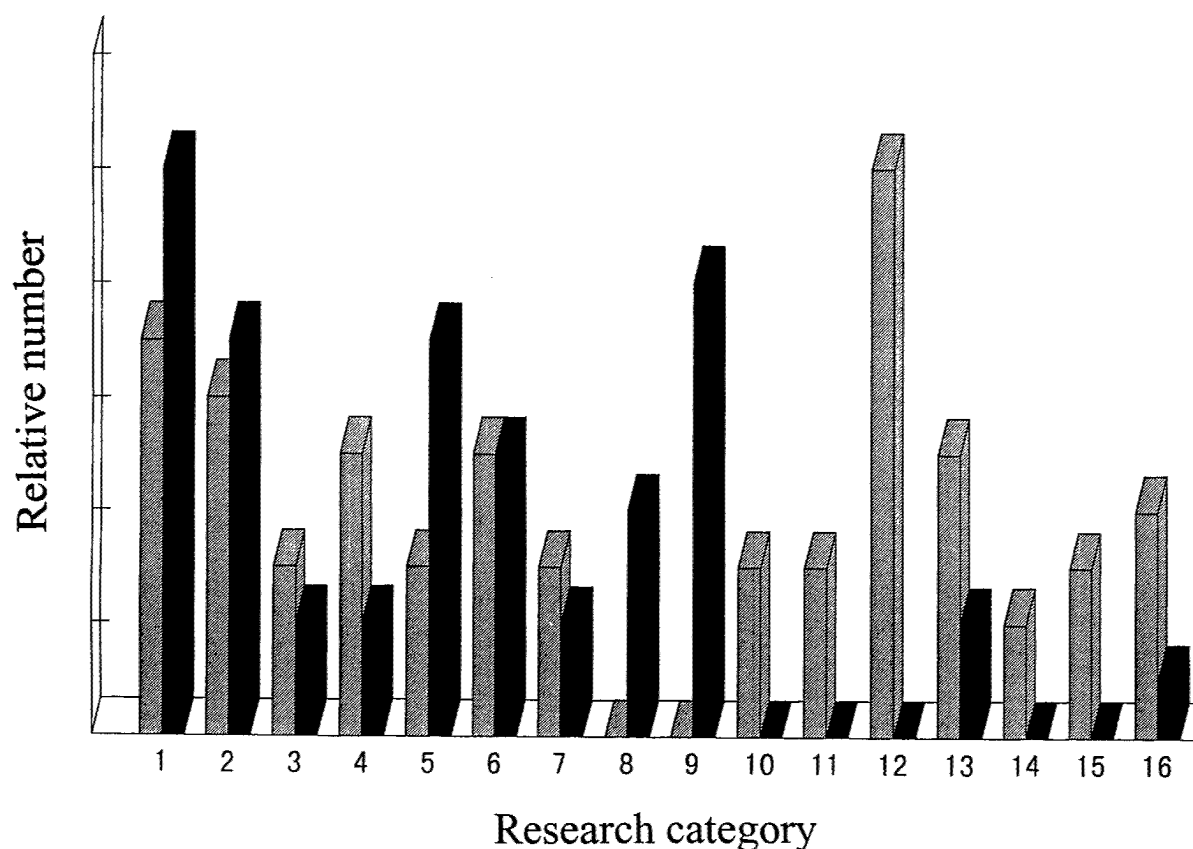


FIGURE 4.1 Relative number of papers published from 1994 to 1998 (see Box 4.3 for definitions of categories 1-16). Light-shaded areas represent the *Journal of the Japanese Society of Naval Architects* of Japan; dark-shaded areas represent the proceedings of the *Symposium on Naval Hydrodynamics* series of the United States. SOURCE: M. Ohkusu, Research Institute of Applied Mechanics at Kyushu University, briefing to the committee October 20, 1999.

As discussed previously, the Department of the Navy transferred more ship design responsibility to the shipbuilding industry as part of Acquisition Reform in the mid-1990s. Industry-government teams were formed to solve short-term design problems, but long-term hydromechanics research is beyond the scope of these teams. Most private shipyards have also begun some hydromechanics research efforts by investing in their IR&D programs. The objectives are to develop their in-house, fast-turnaround CFD design capability and to supplement Department of the Navy R&D so they can improve their competitive positions for new construction contracts. It will take some time before these investments can have an impact on fleet capabilities. It will probably be difficult for the shipbuilding industry to contribute significantly to advancing basic hydromechanics research.

Although the Department of the Navy has always had the main need for hydromechanics research and the main responsibility for it, much of the fundamental research and experimentation in turbulence modeling, analysis, and computational techniques was broadly applicable and developed through collaborative or at least leveraged efforts. Time and circumstances have substantially changed this picture. As fluid mechanics research has been applied to more advanced air and water vehicles, the requirements

have become more specialized and less broadly applicable. High-speed aircraft, nuclear submarines, and surface ships have diverging technology requirements as both the technology and the vehicles become more sophisticated. In addition, in the past 15 years the total of national resources, in real dollars, devoted to fundamental research in engineering has decreased. As a consequence, federal agencies have focused their resources on their highest priorities and unique needs. Collaboration has been more critically viewed as duplication, and only those activities that would not otherwise be addressed have been encouraged. With everyone doing less and focusing on their own identified unique requirements, the ability of the Department of the Navy to leverage its investments in naval hydromechanics has been reduced and the burden for meeting its own future research and technology requirements has increased. The severe consequences of the current environment are obvious from a macroview of agency resource trends in fluid mechanics research:

- According to the resources director of NASA's Aeronautics and Space Transportation Technology Enterprise, the NASA aeronautics base R&T budget and investments in numerical aerodynamic simulation have decreased in constant dollars by 17 percent since 1989 and by 28 percent from their peak in 1993.² Greater emphasis on information science, safety research, and electronic displays and flight controls has reduced aerodynamics investments by a disproportionately large amount. Experimental facilities have been closed and CFD efforts have been reduced. More emphasis is being placed on high-speed and transatmospheric flight, which are less relevant to incompressible phenomena. At the same time, research is focused more in the mid- and near-term, which restricts its applicability.

- The National Science Foundation (NSF) provides support for fundamental research in fluid mechanics and its application in a broad range of disciplines. Recognizing the key role that fluid science plays in almost every human endeavor, from biomedical engineering to river hydraulics and coastline erosion, research support in the NSF Engineering Directorate focuses on those areas in which research would have the broadest application. Challenges for research cover a very broad range of engineering applications, including materials processing and manufacturing; river and coastal engineering; environmental engineering; essentially all forms of transportation, including advanced automotive technology, quieter aircraft, more efficient ships, and economical means for oil transport; a range of issues in medicine that involve fluid dynamics as it relates to almost every organ in the body; and power generation. The ultimate goal of research in this area is to improve our ability to predict and control the fluid motion in all of these situations. Much of this research is generally relevant to naval hydromechanics, but within the very tight budgetary constraints that exist at NSF, fluid mechanics research in the Engineering Directorate should be viewed as complementary to the Navy's S&T program in hydromechanics. These broad areas in fluid mechanics are supported with an annual budget of approximately \$5 million. It is clear that, at these budget levels and with the broad NSF charter, the Navy can rely in only a small way on the NSF to support naval hydromechanics requirements.

- The Air Force Office of Scientific Research has also been a significant contributor to fundamental research in fluid mechanics. Its scope of responsibilities is more narrowly focused on aerodynamics than the broader Navy scope and its emphasis is more closely aligned with that of NASA. It has also seen a reduction in aerodynamics-related funding of approximately 11 percent in constant dollars since FY92.³

²Personal communication on September 9, 1999, between committee member Robert Whitehead and the director of the Resources Management Office, Code R, at NASA headquarters.

³Data provided by Dr. Joseph Janni and Maj Robert P. Crannage, USAF, of the Air Force Office of Scientific Research, December 6, 1999.

- The situation with the Army and the Department of Energy is not markedly different from that with the other agencies, but the impact of these two entities has historically been smaller.

In summary, the Department of the Navy no longer can depend on complementary and leveraged national efforts to significantly support its unique requirements in naval hydromechanics research and technology. It must develop a strategy and sustainable investment plan to independently ensure its future technology and design capabilities in this area.

SCOPE OF NAVY RESPONSIBILITY FOR HYDROMECHANICS RESEARCH

There is a growing requirement for greater stealth, speed, and littoral operations capabilities for planned and future naval surface and subsurface vehicles as well as underwater weapons and sensor platforms. The concepts driven by these requirements will place unprecedented demands on Department of the Navy S&T. Concepts such as Sleek Ship are challenges because the required hull/propulsor system is outside the traditional database used by naval architects, and the geometry and fluid dynamics are complex. As ship signature becomes a higher design priority, the traditional database becomes inadequate. A combination of innovative experiments, computational fluid dynamics, and at-sea measurement programs applied by skilled experts will be the most efficient means by which to establish a new, preliminary database.

Naval hydromechanics is vital to the body of knowledge required for speed, endurance, stealth, maneuverability, and safety issues, with applications for ships, submarines, exotic vehicles, hydroballistics, detection, platforms, tracking, and harbors. This field of fluid science is characterized by several unique factors that are discussed in detail in earlier sections of this report. In his white paper, Marshall P. Tulin provides an excellent overview of the history of these unique requirements and of ONR's role in naval hydromechanics, along with an expert perspective on both past accomplishments and future prospects.⁴ He reminds us that many of the theoretical and analytical techniques that proved so valuable in early developments in aeronautics had their foundations in earlier research and discoveries in hydromechanics.

The Department of the Navy cannot depend on other agencies or the shipbuilding industry to provide these capabilities. Naval hydromechanics is the special purview of naval research, and it is ONR's responsibility to support fundamental research in this area. To achieve the kinds of successes described in this report (and in the supporting material), the Department of the Navy must renew its reservoir of basic knowledge and expertise in naval hydromechanics, which is vital to its long-term interests.

⁴Tulin, Marshall P. 1999. "Naval Hydrodynamics: Perspectives and Prospects." Santa Barbara, Calif: Ocean Engineering Laboratory, University of California. September 14.

Integration with and Transition to Higher-Budget-Category Programs

As defined by ONR, the hydromechanics area consists largely of 6.1 and 6.2 efforts, as shown in Figure 2.1 and Table 2.1 in Chapter 2. For example, in FY99, the total funding of \$24.9 million consisted of \$12 million from 6.1 and \$10.4 million from 6.2, with the small balance from either 6.3 or non-Navy sources. In fact, FY99 is an anomaly in that the 6.2 funding was substantially higher than in any of the preceding 5 years. As explained earlier, this increase was due to a one-time infusion of an additional 52 percent of core 6.2 funds in FY99, which was directed at short-term applications. Over the preceding 5 years, Navy efforts in hydromechanics were funded largely in category 6.1. If such 6.1 efforts are to ultimately significantly increase naval capabilities, they will need to stimulate new 6.2 and 6.3 programs for developing and demonstrating advanced technology to achieve a readiness level appropriate for transition to acquisition programs, and they will also need to be responsive to the research opportunities identified by the 6.2/6.3 efforts. The 6.1 work will be most effective if it contains a balance of exploratory work on very new ideas and very fundamental work in response to opportunities and challenges identified in higher-budget-category programs.

The need for this sort of balance is particularly acute in hydromechanics, which deals with matters that have a large impact on the overall characteristics of ship and submarine platforms: stealth, speed, payload capability, seakeeping/maneuverability, and cost. This means that robust 6.2/6.3 technology development and demonstrations programs, with their emphasis on advanced concepts, are required to underpin the transitioning of significant technology advances to higher budget categories. In addition, significant advances in hydromechanics will require a thorough understanding of the underlying physics as it applies to potential concepts for signature reduction, drag reduction, and other improvements; this is the proper realm of 6.1 research. A long-term 6.2 and 6.3 technology development and demonstration program focused on reasonably well-defined advanced concepts also identifies opportunities and serves as a testing ground for research results. This feedback from technology development to fundamental research is critically important to advancing the state of the art. Two examples will illustrate this point:

- Significant reductions in the sonar self-noise of surface ship bow domes and submarine sonar domes have been achieved over the last several years. The fundamental physics of structural excitation

by turbulent boundary layers has been funded by ONR for many years. This led to an understanding of exponential attenuation of evanescent (nonradiating) hydrodynamic wave numbers, which when applied to the concept of using materials that were inefficient radiators and good transmitters led to rubber- or glass-reinforced plastic domes.

- Currently, a great deal of fundamental hydromechanics research is focused on computational fluid dynamics (CFD) and the treatment of unsolved problems associated therewith: turbulence, separation, cavitation, and free-surface behavior, including bow and transom wave breaking. Such research is important since, clearly, CFD will become more powerful in the years ahead. However, general solutions to the unsolved problems are not imminent, and even if they were, they would not produce advanced platform concepts. A vital strength of such research is its ability to develop techniques that are adequate for the analysis of specific concepts and to perform such analyses. Without clearly defined concepts, there is a danger that CFD research will not be as effective as it otherwise could be (e.g., the study of highly separated flows is a challenging problem but is not particularly relevant to concepts designed to avoid or limit separation).

Certainly ONR and the Naval Sea Systems Command 05H, which includes the Hydrodynamics/Hydroacoustics Technology Center, recognize the importance of advanced concepts. In their presentations to the committee, both organizations emphasized the importance of concept development, with specific reference to advanced shaping, advanced appendages, advanced propulsion, and advanced flow control techniques. Unfortunately, the committee could find no persuasive evidence that there is a currently planned 6.2/6.3 effort to create advanced platform concepts. None of the presentations reported any concerted efforts to explore advanced concepts, either at a subsystem or total system level. Rather, the emphasis is on transitioning design tools for current concepts, which are based primarily on computational fluid dynamics. Improvements in such tools will undoubtedly transition (i.e., be used by designers) once they have been adequately validated; such transitions are important and will at least partially satisfy the perceived pressure for near-term results. However, as noted above, these tools alone are unlikely to lead to significant advances in platform capability. If successful, their largest impact will be to reduce development cost and time.

It should be emphasized that there is no lack of need for advanced technology nor any lack of desire to produce it. In the 1997 NSB study *Technology for the United States Navy and Marine Corps, 2000-2035*,¹ stealth was identified as a fundamental attribute for submarines. Although it was not such a priority for surface ships, signature reduction was considered to be necessary and cost-effective. Additional emphasis on stealth was articulated by the Program Executive Office-Submarines, which called the art and science of designing and building quiet submarine propulsors one of its crown jewels. Moreover, greater affordability—that is, more capability per unit cost—is always needed, and it is an area where hydromechanics can have a significant impact. In the laboratory arena, a recent review by the NSWCCD gave prominence to signature and silencing systems and hull forms and propulsors as its core assets. Yet there does not appear to be an integrated 6.2/6.3 program to bring appropriate concepts to fruition.

One reason for the lack of an integrated 6.2/6.3 program that includes development of advanced platform concepts may be the persistent lack of adequate funding. Table 5.1 and Figure 5.1 show funding for 6.2/6.3 Navy Department ship and submarine technology funding from FY82 through

¹Naval Studies Board, National Research Council. 1997. *Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st-Century Force*, Vol. 6, *Platforms*. Washington, D.C.: National Academy Press.

TABLE 5.1 6.2/6.3 Funding for Department of the Navy Ship and Submarine Hull, Machinery, and Electrical Technology in Then-Year Dollars (millions of dollars)

Year	Program Element				Total
	0602121N Various— Ship/Submarine	0602323N Submarine Technology	0603508N Ship Propulsion System	0603573N Electric Drive	
FY82	41.0	0.0	12.6	0.0	53.6
FY83	NA	NA	NA	NA	NA
FY84	31.1	0.0	41.5	13.4	86.0
FY85	30.2	0.0	47.7	0.0	77.9
FY86	25.3	0.0	30.7	9.8	65.8
FY87	12.5	12.4	10.0	9.8	44.7
FY88	13.0	14.1	14.5	9.0	50.6
FY89	13.3	14.5	14.8	14.0	56.6
FY90	13.8	15.0	0.0	32.1	60.9
FY91	16.0	16.7	0.0	53.8	86.5
FY92	32.0	17.8	4.5	0.0	54.3
FY93	50.1	17.9	4.5	0.0	72.5
FY94	19.3	14.6	3.4	0.0	37.3
FY95	19.9	14.6	3.2	0.0	37.3
FY96	62.9	0.0	18.0	0.0	80.9
FY97	48.7	0.0	31.6	0.0	80.3
FY98	50.4	0.0	49.7	0.0	100.1
FY99	55.5	0.0	52.9	0.0	108.4

SOURCE: All data shown in Table 5.1 are based on the committee's use of documents in the series *Defense Department Appropriations for Fiscal Year* [1982-1999], Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.

FY99. The funding shown in Figure 5.1 is the total of up to four program elements in each fiscal year: 0602121N, currently titled surface ship and submarine technology; 0602323N, now defunct, but titled submarine technology when it existed; 0603508N, which used to be titled ship propulsion system (advanced); and 0603573N, titled electric drive when it was a 6.3 program. The total Department of the Navy 6.2/6.3 investment for all ship and submarine technology in the FY99 President's Budget was about \$100 million per year, which covers efforts in structures, internal machinery, topside signature reduction, and electromagnetic compatibility as well as hydromechanics. Although this level of funding is actually higher than representative annual investments for the past two decades, when the 6.2/6.3 effort averaged about \$70 million per year, it does not seem adequate to conduct the type of technology demonstrations required for advanced platform concepts.

Historically, it appears that the Navy has relied on acquisition program funding to effect large-scale technology demonstrations. In addition, NSWCCD, NUWC, and the Applied Research Laboratory at Pennsylvania State University (ARL/PSU) all noted that the current and projected levels of S&T funding are inadequate to maintain a core capability, to carry out the required fundamental research, and to provide incentives for bright, young graduates to enter the field. For the last two decades, this shortfall in S&T funding has been compensated for, at least in part, by the influx of funds from acquisition programs and, in the case of submarines, DARPA.

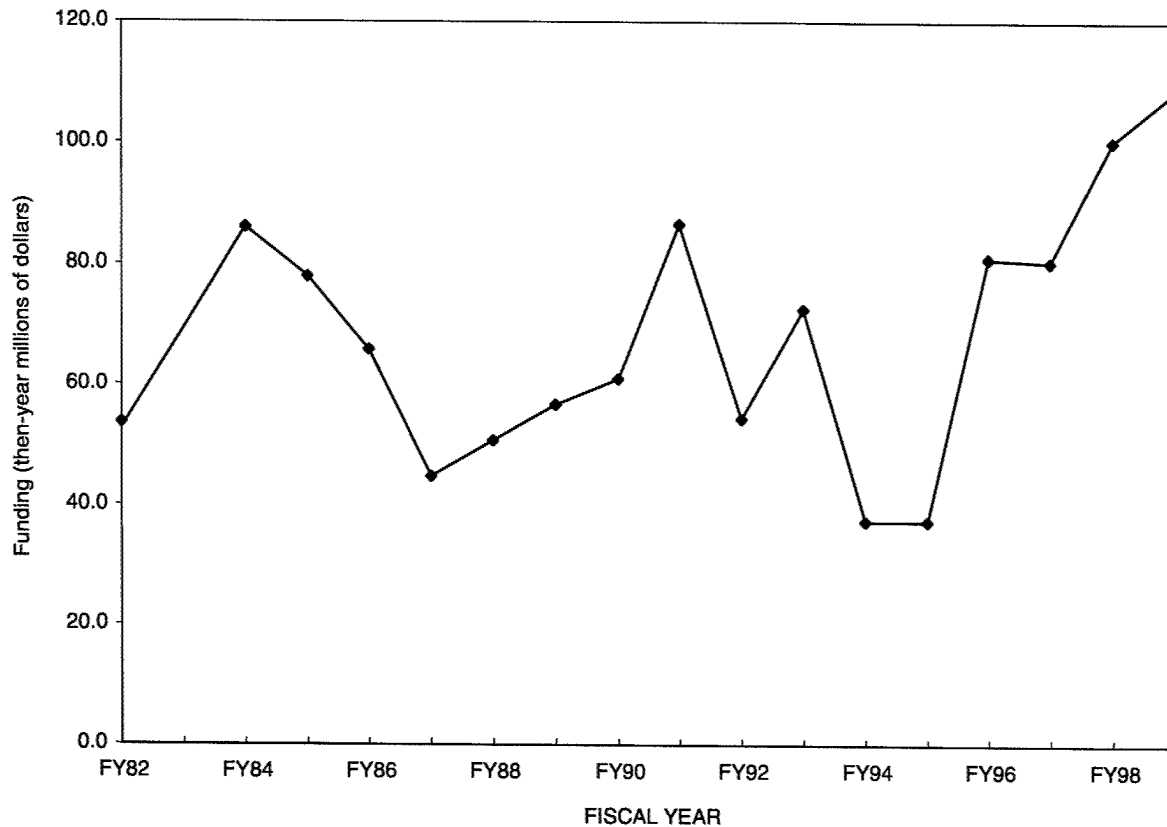


FIGURE 5.1 Department of the Navy 6.2/6.3 ship and submarine HM&E technology funding.

SOURCE: All data shown in Figure 5.1 are based on the committee's use of documents in the series *Defense Department Appropriations for Fiscal Year [1982-1999]*, Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.

There are two types of acquisition funding: one is funding for the development and procurement of major warships; the other is 6.4 funding not directly associated with major acquisitions. There are several difficulties associated with relying on major acquisition funds for technology development and demonstration as well as for maintaining core capabilities. Acquisition funding for the first in a class of new warships, although it is large, is in category 6.4 or higher, in RDT&E or in procurement (ship construction (building and conversion), Navy—SCN). Additionally, the funding is apportioned to the individual acquisition programs keyed to the fiscal year of the lead ship construction contract and usually becomes available, ostensibly to support the total system design, 2 to 3 years before that fiscal year (see Figure 2.2). In general, the funding arrives too late to trigger significant new research and too late to transition anything but very mature work; it cannot be relied on for the high-risk technology demonstrations that are the precursors to large advances. Nonetheless it has some beneficial effects: it brings about some technology transition, some of which was no doubt serendipitous; it encourages frequent communications between research staff and engineering personnel assigned to support the design of a new ship; it provides input from ship designers to ONR on their selection of technology efforts, thereby ensuring their integration in the short term; and it enables the laboratories to remain manned and active. However, there has been a long interval between new classes: for aircraft carriers

almost 40 years, and for submarines and destroyers 10 to 15 years. With the current levels of S&T funding, there will be long, dry periods that can prove disastrous for maintaining a first-class research capability, for advancing the state of hydromechanics technology, and for being able to recruit graduates. Even in the best of times, it is questionable policy to rely on major acquisition funds for the advancement of technology; it is certainly not good policy now.

Category 6.4 funds not associated with major acquisitions do offer greater opportunity for technology demonstration. In the 1970s, the Small Waterplane Area Twin Hull (SWATH) ship concept was matured and developed into the Navy's first stealth surface ship, *Sea Shadow*, by the application of 6.1 and 6.2 funding, supplemented by funding from a then 6.3 program called "Conform." This program would now be funded by a 6.4 line. The Conform program was run by ship design managers who had direct responsibility for adapting the technology into advanced design platforms.

The Conform program had its origin in the mid- to late 1960s, when the Office of the Secretary of Defense (OSD) required all major acquisitions to undergo three systematic phases called concept formulation (Conform): (1) concept exploration and concept development, (2) contract definition, and (3) prototype production. The U.S. Navy was required to go through this process for the LHA and DD 963 classes. Concept formulation was started for the successor submarine class to the SSN 637. This evolved into the preliminary design for the SSN 688 class, which was procured in the old fashion.

It became obvious during the submarine Conform program that there was a serious disconnect between S&T and R&D and the design process. The solution was obvious for future designs: a continuing effort of advanced concept exploration funded as a (then) 6.3 line. This proposal was approved and funded for several years for submarines. It became unfunded but survived as the surface ship 6.3 line described above.

The Navy currently has a submarine technology program funded in acquisition category 6.4. This program is devoted to all aspects of submarine technology—communications, combat systems, weapons, internal machinery, and hydromechanics. Funding for this program is approximately \$40 million per year; current efforts are largely devoted to near-term improvements for the new attack submarine (NSSN), but future efforts will be more aggressive. The program affords ONR an opportunity to formulate a 6.2/6.3 program wherein a substantial amount of technology demonstration could be conducted with 6.4 funds. The fact that the program was not mentioned in any of the presentations to the committee is another indication that in the hydromechanics area, integration with higher-category programs could be improved.

Another reason for the lack of an integrated 6.2/6.3 program aimed at advanced platform concepts—and it may also explain the lack of funds—may be a lack of commitment to pursue the concepts to their logical conclusions. There is no shortage of advanced concepts: trimarans, tumble-home monohulls, high-speed sealift vehicles, planing craft, and submarine platforms with minimal or no appendages, to name a few. Many of these concepts have been postulated for a number of years. All of them entail unknowns in hydromechanics, and most would require advanced concepts at the subsystem level (i.e., shaping, flow control, appendages, and propulsors) if useful vehicles are to result. Two examples at the subsystem level follow:

- When submarines increase their speeds flow-induced noise becomes a major cause of detection and classification by threat sonars. There are a number of contributors to flow-induced noise, including the sail, flood ports, control surfaces, and other discontinuities along the hull. During maneuvers, the acoustic levels are much higher owing to separated flows and enhanced flow distortions. The basic reasons are generally understood, but the flow-acoustic interactions are complex; concepts for noise control are needed if these interactions are to be quantified in a highly relevant manner. For example,

one concept might be to eliminate the sail. While this would of course create a need for other advances, it would eliminate a significant source of radiation noise and reflectivity to active sonar.

- Evolving mission requirements necessitate hull and appendage geometries that often set practical limits to the achievement of important performance parameters. There has been renewed interest in polymer ejection to reduce drag and noise. If they can be further developed and demonstrated at a practical level, the required high-speed signature and maneuvering capabilities may be achieved at much lower acquisition and life-cycle cost.

There are many other examples of the need to pursue advanced concepts in a disciplined way. Yet there was no integrated 6.2/6.3 plan presented to the committee to pursue any one of these concepts to the point where it could be shown to be potentially successful, or alternatively, not worth pursuing further. If significant increases in basic platform capabilities are to be made, they will come only from the pursuit of advanced concepts. It is largely the magnitude of the potential increases in platform capabilities that determines the amount of funding that will be made available. Without a credible, integrated 6.2/6.3 plan to achieve such capabilities, the funding is likely to be inadequate.

Findings and Recommendations

IMPORTANCE OF HYDROMECHANICS RESEARCH TO THE NAVY

Findings

U.S. naval superiority depends critically on the maintenance of leadership in the science and technology that supports the fleet. Hydromechanical performance is fundamental to the basic fighting capability of surface ships and submarines in terms of speed, stealth, seakeeping, endurance, maneuverability, and human performance. These issues have become more important in recent years as the Navy's focus has shifted from the deep ocean to the littoral environment, where new land-based and sea-based threats now must be addressed. Various factors point to the need for increased speed.

While hydromechanics has application in many fields unrelated to naval needs, there are important ways in which naval hydromechanics is unique, especially ways that affect speed and stealth. These include free-surface effects, including breaking bow and stern waves, surface wakes, submarine wakes, cavitation, drag reduction, wave resistance, and added resistance in waves.

In the absence of a strong commercial shipbuilding industry in the United States, there is no other patron but the Navy to lead research in these areas. Therefore, if the United States is to maintain its naval superiority, ONR must assume responsibility for the fundamental R&D leading to hydromechanics S&T that is unique to the Navy's needs, while drawing on the knowledge and technology base from related fields.

Recommendation

To enable the Department of the Navy to maintain superiority in naval hydromechanics and to allow the necessary resources to be devoted to this aim, ONR should designate naval hydromechanics as a National Naval Need.¹

¹As stated by Fred E. Saalfeld to the Office of Naval Research (ONR), National Naval Programs (now called National Naval Needs) are those science and technology areas that are uniquely important to the naval forces and whose health depends on ONR investment. See the preface for additional discussion.

FUNDAMENTAL HYDROMECHANICS RESEARCH

Findings

1. Over the past 20 years there has been a shift away from fundamental research toward applications-driven research with a relatively short-term focus. This shift, apparently driven by budgetary pressures and the desire for immediate transition, threatens to weaken the knowledge base and the pool of scientific talent and hence to decrease the generation of new ideas.

2. There are already disturbing signs of this trend: for example, the reduction in programs at leading research universities, such as the Massachusetts Institute of Technology and the University of California at Berkeley, and in the fundamental hydromechanics research programs at the Navy's laboratories.

3. In the long run, this erosion in the fundamental research program will weaken the future technological leadership of the U.S. Navy.

Recommendations

On the basis of these findings, *the committee recommends the following changes in ONR research policy as it relates to hydromechanics:*

1. *Funding for 6.1 should be less focused on immediate needs and more focused on broad, long-term research on fundamental problems in naval hydromechanics such as linear and nonlinear wave dynamics, including wave breaking, air entrainment effects, and air/sea interactions; all aspects of cavitating and supercavitating flows, including inception, noise, and damage; drag reduction and other aspects of flow control; surface and submerged wakes; hydrodynamic sources of noise; internal wave generation and propagation; and vortex dynamics and turbulence unique to naval surface and subsurface vehicle/sea interaction.*

2. *The 6.1 resource base should be stable and should be protected from the larger funding fluctuations associated with major acquisition programs.*

3. *In the 6.1 area, ONR should promote a culture of bottom-up research, which can bring novel developments and lead to solutions for unanticipated problems that may arise in the future.*

INTEGRATION AND TRANSITION

Findings

1. Current ONR hydromechanics efforts are not well coordinated with higher-category technology development and demonstration efforts, for two main reasons. First, there does not appear to be a long-term vision for advanced concepts for ship and submarine platforms, so there is no well-defined 6.2/6.3 program plan with which to coordinate. Nor is there an equivalent to the Conform program of the 1970s, which contributed to the successful development of the *Sea Shadow*. Second, there is not enough S&T funding to pursue a robust technology development and demonstration program aimed at new platform concepts. This lack of funding is not new. For at least two decades, science and technology (6.1, 6.2, 6.3) funding in ship and submarine technology in general and hydromechanics in particular has been inadequate to support such a program. In the past, S&T funds were supplemented by the periodic infusion of major acquisition funding, which filled the voids and sustained research expertise at the same time as it responded to the needs of the acquisition managers. This reliance on major acquisition funding for S&T activities served as a deterrent to longer-term, more aggressive activities.

2. The lack of a long-term vision for what advanced ship and submarine platforms would offer in improved signature, speed, cost, and payload capability or the lack of an integrated 6.2/6.3 plan to achieve the necessary overall hydromechanical concepts will have significant consequences: funding will remain inadequate, there will be a lack of focus for 6.1 efforts, it will be difficult to sustain expertise and attract new graduates, and the future naval capability by the United States will suffer.

Recommendations

1. *ONR, in conjunction with the relevant Office of the Chief of Naval Operations and the Naval Sea Systems Command/Program Executive Office organizations, should formulate and maintain an integrated 6.2/6.3 plan for technology development and demonstration aimed at new platform concepts for ships and submarines and using the results of long-term basic research under ONR sponsorship. Key features of this plan should include (1) significant advances in a 15-year time frame, (2) clearly articulated goals in the related hydromechanics areas of signature reduction, drag reduction, propulsive efficiency, and seakeeping/maneuverability, and (3) the examination of concepts that could achieve these goals. Demonstrations necessary to ensure the validity of predicted performance should be described. The investment required and the resulting payoffs in terms of improvements in stealth, speed, cost, and payload capability should be assessed. The plan should guide 6.2/6.3 research and development efforts. The planning process should involve experts from the industry that engineers and builds naval systems; these experts must have long-term vision. The plan should also (1) require and accommodate innovative and competing approaches, (2) foster collaboration between the Department of the Navy, academia, industry, and, where appropriate, foreign organizations, (3) identify opportunities for areas of fundamental research, and (4) stimulate concepts for spin-off to commercial applications.*

2. *Continuous channels of communication should be established between the research, design, and operations communities to ensure the effective use of research results and to inform researchers of specific problems as they arise. It is anticipated that improved communications at the Department of the Navy and between the department and the industrial and academic communities will lead to a stronger research program with significant future payoffs for the Department of the Navy.*

NAVY'S ASSETS FOR HYDROMECHANICS RESEARCH

Findings

1. There are numerous Navy test facilities. Some are new (e.g., the large cavitation channel at NSWCCD) and some are fairly old (the Garfield Thomas water tunnel at ARL/PSU and the facilities at NSWCCD). Some facilities are not fully utilized. Some towing basins would be busier were it not for the fact that the maritime industry in the United States is progressively declining, and many potential users from the United States and abroad turn to overseas facilities.

2. Each center is operated independently of the others. Each has unique features, but there is also some substantial overlap. There seems to be inadequate funding even for upkeep, let alone improvement and modernization. Instrumentation is very basic and in general targets design data rather than flow physics. There seems to be no significant program to upgrade the existing instrumentation.

3. The successful utilization of test facilities depends heavily on their quality and condition. This is controlled by the repair and maintenance (R&M) program. Currently, R&M is funded by organizational overhead funds or a direct surcharge to the project using the facility. This translates to increased project

costs to the customer in either case. The transfer of work to European facilities is motivated by their lower costs and better service. The S&T program could benefit significantly if the cost of hydromechanics testing in the United States could be cut, encouraging the use of U.S. facilities.

4. The primary function of the existing Navy laboratories (other than the Naval Research Laboratory (NRL)) is to support the development of new naval platforms and weapons. A relatively small fraction of each center's efforts is directed at fundamental research. In some cases the size of the scientific staff working on fundamental problems seems below critical mass, and groups in the different centers appear to be working in isolation. The overall management philosophy is geared toward developmental activities and does not nurture fundamental research.

5. Responsibility for the technical management of development work on advanced platforms and weapons has shifted from the centers to the ONR program managers. This dilutes the support for fundamental research in fluid mechanics at ONR and has led to a reduction of the basic research effort.

Recommendations

The Department of the Navy should take the following steps to ensure that high-quality S&T is conducted at the hydromechanics research centers:

1. *The Department of the Navy should consider retiring some of the less advanced facilities at the centers so that the rest can be improved and supported by better technical know-how and more manpower.* Facilities that have shown no significant work or major instrumentation upgrades for a long time (say, 10 years) should be considered for decommissioning.

2. *The Department of the Navy should aggressively pursue advanced measurement techniques (e.g., noninvasive, holographic, ultrasonic, and velocimetry techniques).*

3. *The maintenance and upgrade of hydromechanics facilities at the Department of the Navy centers should be funded from a separate source not linked to the S&T program.*

4. *The fundamental basis for experimental work at the Department of the Navy's centers should be strengthened.* Experts from the different centers should be involved in intercenter scientific committees promoting the scrutiny and discussion of issues such as design and upgrade of facilities, qualification and documentation of the characteristics of an adequate facility, development and acquisition of new instrumentation and measurement techniques, physical interpretation of data, and evaluation of the scientific merit of the proposed experiments and the results obtained. Funding allocations should be based not only on the merit of proposed work but also on a track record of significant contributions from past work. The high quality of the Department of the Navy centers can be maintained by regular internal and external peer review and emphasis on the refereed publication of research results.

5. *A more active collaborative relationship between university and center researchers should be facilitated to take advantage of the strengths of both and create a stronger overall research effort.* Top-notch researchers from universities and other research institutions should be involved in research at the centers. The centers should use university researchers as active members of working teams in technical and scientific matters, design, facility upgrades and modifications, instrumentation design, and data presentation and interpretation of results. In addition, facilities and their use should be subjected to periodic evaluation by teams of external experts.

6. *The quality of the research and technical management staffs should be improved over time by providing a more attractive research environment for the best and brightest university graduates.*

AN INSTITUTE FOR NAVAL HYDRODYNAMICS

Findings

1. Recent changes in the missions of the Navy and Navy-funded laboratories have emphasized fleet and design support at the expense of research in naval hydromechanics.
2. Budgetary considerations have further restricted the number of researchers and the scope of the research that can be performed at a single location. However, there is still a large body of enthusiasm and intellectual talent, although it is widely dispersed.
3. Modern means of communication provide new, unexploited opportunities to enhance scientific interactions between geographically separate groups of scientists and engineers. Databases, experimental facilities, libraries, and intellectual talent can be accessed instantaneously and without time-consuming interruptions.
4. Currently there are no centers of excellence for fundamental research in naval hydromechanics.

Recommendations

1. *ONR should establish an institute for naval hydrodynamics (INH).*
2. *The INH should capture the best talents and the largest body of knowledge in hydromechanics from the United States and foreign countries. It should leverage existing funding and ensure a well-coordinated approach to research in hydromechanics.*
3. *The INH should be directed by a highly qualified scientific leader. The management style and philosophy should be in tune with the intellectual creativity expected of participants in the INH.*
4. *A small central facility should support the INH. This facility should be open to all INH participants.*
5. *The form of the center should be carefully determined. One attractive option would be a virtual center that uses distributed assets and extensive Internet communication. The virtual center would have a management committee and a small central supporting entity. The new NASA Astrobiology Institute organized by the NASA/Ames Research Center, the European Research Community on Flow, Turbulence, and Combustion, and the NASA Institute for Advanced Concepts are models for virtual centers. Virtual centers could draw upon researchers from anywhere at any time. Although the idea is relatively new and relatively untested, it is very promising, and the committee recommends that it be given serious consideration. Alternatively, the center could be modeled after the jointly managed NASA/Stanford Center for Turbulence Research and the independently managed Institute for Computer Application Science and Engineering, at NASA/Langley.*

Appendixes

A

Research Facilities and Equipment for Naval Hydromechanics Technology

NATIONAL ASSET HYDROMECHANICS TEST FACILITIES

Naval Surface Warfare Center, Carderock Division Facility Summary

Two parallel towing tanks are located at the Naval Surface Warfare Center, Carderock Division (NSWCCD), in Carderock, Maryland. One tank is subdivided by a bulkhead to provide two independent basins with separate carriages. The first basin includes a deep section 6.7 m deep, 271 m long, and 15.5 m wide, and a shallow section 3 m deep, 92.4 m long, and 15.5 m wide. The carriage has a maximum speed of 9.3 m/s. The adjoining second basin is 6.7 m deep, 575 m long, and 15.5 m wide, with a pneumatic wave maker at one end and a wave-absorbing beach at the other. The carriage in this basin has a maximum speed of 10.3 m/s. The other towing tank, known as the high-speed basin, is 904 m long with a deep section 4.9 m deep, 514 m long, and 6.4 m wide and a contiguous shallow section 3 m deep, 356 m long, and 6.4 m wide. A pneumatic wave maker is at the deep end and an absorbing beach is at the shallow end. Two carriages are located in the high-speed basin, with maximum speeds of 16.5 m/s and 25.7 m/s.

The maneuvering and seakeeping basin is 110 m long by 73 m wide with a depth of 6.1 m except for a 10.7 m deep by 15.2 m wide trench parallel to the long side of the basin. Two banks of pneumatic wave makers are located along the length and width of the basin. The wave makers can generate waves up to 0.6 m in height and from 0.9 to 12.2 m in length. Both regular and irregular waves can be generated. The basin is spanned lengthwise by a bridge supported on a rail system that permits the bridge to traverse one-half the width of the basin and rotate 45 degrees from the longitudinal centerline of the basin. The carriage, supported under the bridge, has a maximum speed of 7.7 m/s.

The rotating arm basin is 79.2 m in diameter and 6.1 m deep. The bridgelike arm has an undercarriage that can be set to a specific test radius. Steady-state speeds of 15.4 m/s can be obtained in one-half

revolution at the 36.6 m radius. Speeds up to 25.7 m/s can be obtained at the same radius in two revolutions.

The circulating water channel is a free surface, closed-circuit channel. The test section is 2.7 m deep, 18.3 m long, and 6.7 m wide. The maximum speed is 5.1 m/s.

The 36 in. variable-pressure water tunnel has a recirculating, closed circuit with a resorber and two interchangeable circular test sections, an open jet, and a closed jet. The maximum speed is 25.7 m/s and the pressure range is 414 kPa to 14 kPa. Propeller dynamometers are located on the upstream and downstream shafts, along with a right-angle drive dynamometer and an inclined-shaft dynamometer.

Lake Pend Oreille is in northern Idaho. Its main physical attributes are as follows: depths of $1,150 \pm 5$ ft over approximately 26 mi²; ambient noise 10 to 15 dB below sea state zero, with 25 percent probability (night); isothermal at 39.5° F below the surface layer; 0.02 knot current below 100 ft; standard deviation of transmission loss fluctuations 0.3 dB at 10 kHz and 1 kyd; volume reverberation of -39 dB dropping to -53 dB in 0.3 s; and active sonar pulses reflected from models received before reflections from lake boundaries. Major test facilities include large-scale models of submarines as well as small, laboratory-size objects for fundamental research. Powered or buoyantly propelled large-scale models provide data at Reynolds, Froude, and Helmholtz numbers that closely approximate full-scale values. Although mechanical damping cannot be scaled, data acquired over many decades on several classes of submarines provide guidance for model design. The Large Scale Vehicle (LSV) is a 1/4-scale powered model of the SSN 21 submarine. This unmanned vehicle travels at commanded depths and speeds over an instrumented range where its radiated noise is measured. The output of 2,000 on-board sensors is simultaneously recorded. A second vehicle, LSV II, a 1/4-scale model of the Virginia class, is scheduled for delivery in 2000. The intermediate-scale measurement system, installed in 1995, is designed to obtain precision measurements of the low- and mid-frequency active and passive acoustic signature characteristics of large submarine models. The system includes transmit and bistatic receive arrays capable of synthesizing farfield plane waves. The onboard data acquisition system contains over 1,000 channels as well as a 34-channel hull excitation system. Experiments can be remotely controlled and data can be processed in real time. Secure data links to Carderock allow scientists access to data, thereby creating a virtual laboratory.

The Large Cavitation Channel is located in Memphis, Tennessee. It is a closed-circuit, closed-jet test section 3 m wide, 3 m deep, and 13 m long, with a very low acoustic background level. The working maximum velocity is 18 m/s, with an absolute pressure range of 3.5 to 414 kPa.

Naval Undersea Warfare Center Facility Summary

The Naval Undersea Warfare Center (NUWC) acoustic wind tunnel, suitable for both internal and external studies, is a low-noise (-40 dB at 100 Hz) facility for hydroacoustic, boundary layer turbulence, and wake studies. The 48-in. diameter, 108-in. long test section of the anechoic (100 Hz to 40 kHz) closed jet has a speed range of 0 to 200 ft/s, with turbulence intensity less than 0.3 percent and exit flow uniformity greater than 99.5 percent. Its 78-in. diameter, 500 hp, 14-in. diameter blower is mounted on 160-ton concrete for vibration isolation. It has instruments for flow visualization, high-speed photography, and acoustic measurements, and is supported by rapid model prototyping using stereolithography.

The Langley seawater tow tank (2,880 ft long, 24 ft wide, and 12 ft deep), which is owned by NASA and operated by NUWC, enables testing in both fresh- and saltwater (14 to 18 parts per thousand) environments. With a speed range of 0 to 68 ft/s, it is capable of full-scale, six-component load testing. A retractable gate allows the first 50 ft of the tank to serve as a drydock during model installation and

maintenance. The tow tank is also used for unmanned underwater vehicle launch, maneuvering, and recovering, and supercavitating vehicle studies.

The NUWC research tow tank (90 ft long, 4 ft wide, and 3 ft deep), which can employ either fresh- or saltwater as its medium, has a speed range of 2 to 10 ft/s. A retractable gate allows the first 15 ft to be used as a drydock during model installation and maintenance. The last 60 ft of the tank provide visual access.

The NUWC research water tunnel (1 ft \times 1 ft, 10-ft test section) employs either fresh- or saltwater and is used for medium-scale studies in fully developed duct flow, boundary layer (drag control, separation, reattachment), and cavitation. The tunnel operates at a speed of up to 30 ft/s with a turbulence level less than 0.5 percent.

The NUWC quiet water tunnel (acoustically quiet above 30 Hz) is well suited for the measurement of pseudosound and flow-induced noise and allows three different configurations of the test section: circular (1.75 in. and 3.5 in. diameter), square (1.1 in. \times 1.1 in. and 2.2 in. \times 2.2 in.), and rectangular (12 in. \times 4.4 in.). Up to the maximum centerline speed of 55 ft/s, the facility enables wall pressure (piezoelectric) and velocity vector (hot film and laser Doppler anemometer) measurements with 48 channel data acquisition at 5 kHz.

ACTIVE ACADEMIC TEST FACILITIES

Applied Research Laboratory/Pennsylvania State University Facility Summary

The Garfield Thomas water tunnel (closed-loop, closed-jet; 48 in. diameter, 9.27 m long) can operate at a speed of up to 18 m/s at a turbulence level of 0.1 percent, and its air content can be controlled to below 1 ppm. This tunnel is used for steady and time-dependent force and torque measurements on powered models with a diameter of up to 63.5 cm and for measures of their cavitation performance.

The cavitation tunnel (closed-loop, closed-jet) operates in two configurations: circular (12 in. diameter, 30 in. long) and rectangular (20 in. \times 4.5 in., 30 in. long) with speeds up to 24.38 m/s. It is used for steady and time-dependent pressure, force, and cavitation noise measurements on unpowered models (up to 2 in. diameter).

The 6 in. cavitation tunnel (closed-loop, closed-jet) operates at a speed of up to 21.34 m/s and is used for studies of cavitation phenomena and axial-flow pump performance.

The ultrahigh-speed cavitation tunnel (closed-loop, closed-jet) uses water, freon 113, or alcohol at a speed of up to 83.8 m/s and is used for incipient and desinent cavitation studies.

The subsonic wind tunnel (closed-loop) has a 1.219 m \times 4.88 in. test section and can operate at speeds up to 45.72 m/s with a turbulence level less than 0.2 percent. It is used for studies of boundary layers, wakes, and wall-wake interactions.

The cascade facility (35.5 cm \times 3.5 cm) can operate at a speed of up to 36.6 m/s with a turbulence level of less than 0.2 percent and is used for basic research in turbomachinery blading.

The boundary layer research tunnel (30.2 cm diameter, 7.6 in. long) operates at a speed of up to 9 m/s. The working medium is glycerine, allowing detailed measurements in turbulent boundary layers over a wide Reynolds number range as well as in a viscous sublayer structure.

The axial flow research fan (open-circuit or in conjunction with a flow-through anechoic chamber) is used for studies of turbomachinery noise and vibration and can operate at flow-through velocities up to 34.14 m/s and relative velocities up to 91.44 m/s.

The flow-through anechoic chamber (9.3 m high \times 5.5 m wide \times 6.8 m deep working volume) has a cutoff frequency of 70 Hz and is used for basic research in turbomachinery, active and reactive acoustics for air moving and cooling systems, and scale model testing of proposed auditoriums.

The quiet wall jet facility (open-circuit, open-jet, with or without flat plate) operates at a speed of up to 35 m/s. Its blower is located in a sound and vibration isolation box and is provided with a muffler at intake. It is used for radiated sound studies of boundary layers and separated flows.

The high Reynolds number pump facility (five-row, axial flow) is used within the test section of the Garfield Thomas water tunnel for blade-to-blade flow-field and cavitation studies in blade tip/end wall regions. It operates at speeds of up to 15.5 m/s and blade Reynolds numbers of up to 6×10^6 .

The centrifugal pump test facility (closed-circuit, quiet, noncavitating control valve) has an inlet casing of 12 in. diameter and an exit casing of 29 in. diameter. It is used for pump performance studies, including acoustic and vibration measurements.

University of Michigan

The University of Michigan towing tank is located in Ann Arbor, Michigan. It is a 6.7 m wide, 3.05 m deep, and 109.7 m long basin with a plunger wave maker at one end and a wave-absorbing beach at the other. The carriage has a maximum speed of 6.1 m/s. The wave maker can generate waves 0.25 m high and up to 8 m in length.

University of New Orleans

The University of New Orleans towing tank is located in New Orleans, Louisiana. The tank is 4.6 m wide, 2 m deep, and 38.3 m long with a flap-type wave maker at one end and a wave-absorbing beach at the other. The carriage has a maximum speed of 3.66 m/s. The wave maker can generate regular, transient, and irregular waves with a maximum height of 0.5 m and wavelengths of 0.3 to 22 m.

U.S. Naval Academy

The U.S. Naval Academy towing tank is in Annapolis, Maryland. The tank is 7.92 m wide, 4.87 m deep, and 117.5 m long with an articulated-flap wave maker at one end and a wave-absorbing beach at the other. The low-speed carriage has a maximum speed of 7.6 m/s and the high-speed carriage has a maximum speed of 14 m/s. The wave maker can generate regular, irregular, and transient waves up to 1 m high and 1 to 30 m long.

Texas A&M, University of Texas

The Offshore Technology Research Center is a National Science Foundation engineering research center jointly operated by Texas A&M University and the University of Texas. The basin is in College Station, Texas, and is 45.7 m long, 30.5 m wide, and 5.8 m deep. An adjustable-depth pit is located in the basin, which is 9.1 m long, 4.6 m wide, and 5.8 to 16.8 m deep. The wave maker consists of 48 articulated flaps capable of producing regular, irregular, focused, and short-crested waves. Waves up to 0.9 m in height with a period of 0.5 to 4.0 s can be produced. A current of up to 0.6 m/s can be generated.

University of Minnesota

The Saint Anthony Falls Laboratory (SAFL) of the University of Minnesota in Minneapolis is equipped with three water tunnels. The 6-in. water tunnel was originally designed to model the NSWCCD 36-in. water tunnel. The tunnel is currently modified to have a 190 mm \times 190 mm test section and a maximum flow speed of about 8 m/s. The 10-in. free jet water tunnel was specially designed to perform studies of supercavitating flow at very low cavitation number, of the order of 0.01. The maximum attainable velocity is about 15 m/s. This tunnel has a unique design. A free jet of about 250 mm (10 in.) in diameter and 1,000 mm long is created in a test section approximately 600 mm in overall diameter. This water tunnel has a nonrecirculating flow that aspirates the test section in passing through it, thus providing a convenient means of obtaining reduced test section pressures. The 1,270 mm long high-speed water tunnel is a recirculating flow facility with a 190 mm \times 190 mm test section. It can be operated in either a free surface mode or a closed jet mode at a maximum speed of 30 m/s with a turbulence level of less than about 0.3 percent. The maximum test section pressure is 4 bars. The tunnel has several unique features, including a special gas removal system that can remove as much as 4 percent by volume of injected air. This allows the gas content in the tunnel to increase from 2 to 15 ppm in about four hours. In its present operating mode, the test section also has a separate acoustic tank containing an array of hydrophones for acoustic studies. The tunnel is equipped with a special vortex nozzle to measure the tensile strength of the water, a phase Doppler anemometer for bubble size measurements, a laser Doppler anemometer system, and a force balance. It is driven by a 150 hp motor and has a specially designed and built axial flow pump that is extremely quiet and highly resistant to cavitation.

The SAFL also has a multipurpose main test channel. This is the highest capacity open channel facility in the laboratory (76 m long \times 2.7 m wide \times 1.8 m deep). It has its own intake structure that is capable of inflows up to 8.5 m³. The channel can be used either as an open channel with flow depth controlled by a downstream tailgate, as a towing tank, or as a wave tank. This facility has a towing carriage that operates at a constant velocity up to 6.1 m/s. The wave maker can make waves up to 1 m (peak to trough). Boundary layer research with zero background noise can be conducted in the SAFL rising body facility, consisting of a vertical standpipe 24 m high and about 1 m in diameter. A wire-guided buoyant body can be released at the bottom and captured at the top.

California Institute of Technology

The facilities at the California Institute of Technology in Pasadena, California, include three water tunnels. The high-speed water tunnel has two working sections—0.3 m diameter circular and rectangular with walls adjustable up to 0.15 m wide \times 0.76 m high. Maximum velocities in these sections are about 27 m/s and 18 m/s, respectively. Pressure can be varied over the range from vapor pressure to 2 atm. The free surface tunnel has a square section 0.5 m \times 0.5 m and a maximum velocity of about 7 m/s. The low-turbulence tunnel has a test section 0.3 m \times 0.3 m, a maximum velocity of 8.5 m/s, and pressure variable from 0.1 to 1.3 atm. This tunnel has a right-angle drive for propeller observations.

Massachusetts Institute of Technology

The Massachusetts Institute of Technology marine hydrodynamics water tunnel, in Cambridge, Massachusetts, has a closed-jet test section 0.5 m \times 0.5 m \times 1.5 m long with large viewing windows. The maximum velocity is 10 m/s and the minimum pressure is 0.1 atm. The tunnel can be operated with

a free surface or fully flooded. Instrumentation includes an updated LDV system for in-depth flow field measurement and correlation with theory for both propellers and foil sections. The latest addition is a special test section for waterjet pump performance analysis.

University of Iowa

The Iowa Institute of Hydraulics Research at the University of Iowa in Iowa City, Iowa, has a towing tank 3 m wide, 3 m deep, and 100 m long. The drive carriage and model trailer are cable-driven, with a speed range of 0 to 3 m/s. The drive carriage houses equipment for conventional analog-digital data acquisition such as dynamometers, wave gauges, and multihole pitot probes. There is also instrumentation on board for particle image velocimetry (PIV) data acquisition including a PIV vector processor and hardware for automated movement of traverses for equipment (sensor) positioning. The instrumentation includes a four-channel dynamometer; linear potentiometers for model attitude measurement; capacitance, acoustic, and servo-mechanism probes for wave elevation measurements; differential pressure transducers and multihole pitot probes for flow-field velocity and pressure measurements; and a towed PIV system. The wave maker is capable of generating regular and irregular waves, with wavelengths of 0.25 to 6 m and amplitudes of 0 to 15 cm.

B

Meeting Agendas

**SEPTEMBER 14-15, 1999
WASHINGTON, D.C.**

Tuesday, September 14, 1999

Closed Session (Committee Members and NRC Staff Only)

- 0900 CONVENE—WELCOME, INTRODUCTIONS, COMPOSITION AND BALANCE DISCUSSION**
Prof. William C. Reynolds, Chair
Dr. Ronald Taylor, NSB Director
Dr. Joseph T. Buontempo, Program Officer

Open Session

- 1030 ONR INTRODUCTORY REMARKS AND HYDROMECHANICS S&T PROGRAMS**
Dr. Spiro G. Lekoudis, Head, Engineering, Materials, and Physical S&T Department, Office of Naval Research
Dr. Edwin P. Rood, Program Officer, Office of Naval Research
Dr. Patrick Purtell, Program Officer, Office of Naval Research
- 1300 FUTURE NAVAL CAPABILITIES**
Dr. Ronald A. DeMarco, Associate Technical Director, Office of Naval Research
- 1400 ONR HYDROMECHANICS S&T PROGRAMS (CONTINUED)**
Dr. Edwin P. Rood, Program Officer, Office of Naval Research
Dr. Patrick Purtell, Program Officer, Office of Naval Research

1530 RESEARCH AT CARDEROCK

Dr. William B. Morgan, Associate Director and Directorate Head for Hydromechanics, Naval Surface Warfare Center, Carderock Division

Wednesday, September 15, 1999

Closed Session (Committee Members and NRC Staff Only)**0800 NAVSEA**

CDR Amy Smith, USN, Technical Director, Hydrodynamics/Hydroacoustics Technology Center, Naval Sea Systems Command

0900 RESEARCH AT NAVAL RESEARCH LABORATORY

Dr. Jay P. Boris, Chief Scientist and Director, Laboratory for Computational Physics and Fluid Dynamics, Naval Research Laboratory

Dr. William C. Sandberg, Deputy Director, Laboratory for Computational Physics and Fluid Dynamics, Naval Research Laboratory

1030 FUNDAMENTAL RESEARCH ISSUES

Prof. Marshall P. Tulin, Mechanical and Environmental Engineering

Director, Ocean Engineering Laboratory, University of California, Santa Barbara

Closed Session (Committee Members and NRC Staff Only)**1300 FUTURE STUDY PLANS AND ISSUES TO BE ADDRESSED**

Prof. William C. Reynolds, Chair

**OCTOBER 20-21, 1999
WASHINGTON, D.C.**

Wednesday, October 20, 1999

Closed Session (Committee Members and NRC Staff Only)**0800 CONVENE**

Prof. William C. Reynolds, Chair

Open Session**0830 CURRENT STATUS OF SHIPBUILDING ACTIVITIES AND DEPENDENCE ON PROGRESS IN HYDRODYNAMICS**

Mr. James A. Fein, Naval Sea Systems Command

0930 HYDROACOUSTICS RESEARCH

Prof. Ira Dyer, Massachusetts Institute of Technology (Emeritus)

1030 HYDROMECHANICS RESEARCH AT ARL/PSU

Dr. Michael L. Billet, Applied Research Laboratory/Pennsylvania State University

Data-Gathering Session Not Open to the Public

- 1300 **HYDROMECHANICS RESEARCH AT ARL/PSU**
Dr. Michael L. Billet, Applied Research Laboratory/Pennsylvania State University
- 1330 **FUTURE NAVAL REQUIREMENTS FOR HYDROMECHANICS/HYDROACOUSTICS S&T**
Dr. William K. Blake, Naval Surface Warfare Center, Carderock Division
- 1415 **SURFACE SHIP HYDRODYNAMIC NEEDS AND ELECTROMAGNETIC SIGNATURE ISSUES**
Dr. Arthur M. Reed, Naval Surface Warfare Center, Carderock & NAVSEA Signatures Group
- 1500 **USE OF VISCOUS CALCULATIONS FOR NAVY APPLICATIONS**
Dr. Joseph J. Gorski, Naval Surface Warfare Center, Carderock Division
- 1545 **UNDERSEA TACTICAL VEHICLE HYDROMECHANICS OVERVIEW**
Dr. James C. Meng/Dr. Paul J. Lefebvre, Naval Undersea Warfare Center, Newport Division
- 1600 **UNDERSEA FLIGHT HYDRODYNAMICS**
Dr. Stephen A. Huyer, Naval Undersea Warfare Center, Newport Division
- 1625 **UNDERSEA VEHICLE FLOW CONTROL**
Dr. Promode R. Bandyopadhyay/Dr. Charles H. Beauchamp, Naval Undersea Warfare Center, Newport Division
- 1650 **UNDERSEA STEALTH**
Dr. John F. Grant/Dr. Stephen R. Snarski, Naval Undersea Warfare Center, Newport Division
- 1715 **REVOLUTIONARY SUPERCAVITATING VEHICLES**
Dr. Thomas J. Gieseke/Mr. John Castano/Dr. Abraham N. Varghese, Naval Undersea Warfare Center, Newport Division

Open Session

- 1300 **INTERNATIONAL RESEARCH IN HYDROMECHANICS**
Prof. Odd Faltinsen, Norwegian University of Science and Technology
- 1430 **INTERNATIONAL RESEARCH IN HYDROMECHANICS**
Prof. Makoto Ohkusu, Research Institute of Applied Mechanics, Kyushu University
- 1615 **MOBILE OFFSHORE BASE**
Mr. Gene M. Remmers, Office of Naval Research
Dr. Paul Palo, Naval Facilities Engineering Service Center

Thursday, October 21, 1999

Closed Session (Committee Members and NRC Staff Only)

- 0800 **FUTURE STUDY PLANS AND ISSUES TO BE ADDRESSED**
Prof. William C. Reynolds, Chair
- 1300 **FUTURE STUDY PLANS AND ISSUES TO BE ADDRESSED (CONTINUED)**
Prof. William C. Reynolds, Chair

C

Committee Biographies

William C. Reynolds (Chair) is the Donald W. Whittier Professor of Mechanical Engineering at Stanford University. He received his BS, MS, and PhD degrees in mechanical engineering from Stanford University in 1954, 1955, and 1957 and has been a member of the Stanford faculty of mechanical engineering since 1957. He served as the department chair in 1972-1982 and again in 1989-1993. His research has covered a broad range of experimental, analytical, and computational fluid dynamics and applied thermodynamics. He has played a key role in the establishment of several interdisciplinary research activities at Stanford. He was the founding director of the Institute for Energy Studies at Stanford in 1974-1980 and was co-director of the Stanford Integrated Manufacturing Association (SIMA) in 1990-1993. Dr. Reynolds has been a principal faculty leader in the NASA/Stanford Center for Turbulence Research and is the founding director of the new Center for Integrated Turbulence Simulations. His honors include two Stanford awards for teaching excellence, an American Society of Electrical Engineers (ASEE)/American Society of Mechanical Engineers (ASME) award for contributions to teaching and research, the Fluids Engineering Award of the ASME (1989), the Otto Laporte Prize of the American Physical Society (APS) Division of Fluid Dynamics (1992), the Fluid Dynamics Prize of the American Institute for Aeronautics and Astronautics (1999), election as fellow of ASME and APS and associate fellow of the American Institute of Aeronautics and Astronautics (AIAA), and election to the National Academy of Engineering (1979) and the American Academy of Arts and Sciences (1994).

Roger E.A. Arndt is a professor of civil engineering at the University of Minnesota. After working in industry on supercavitating underwater rockets and high-speed marine vehicles, he began his academic career at Pennsylvania State University in 1967 with a dual appointment in aerospace engineering and the Garfield Thomas water tunnel of the Applied Research Laboratory. He moved to the University of Minnesota in 1977 as the director of the Saint Anthony Falls Laboratory. He has also served as the chairman of the Fluid Mechanics Program in the Graduate School. While on loan to the National

Science Foundation from 1995 to 1998, he was director of the Fluid Dynamics and Hydraulics Program. His research experience is in aero- and hydroacoustics, cavitation, turbulent shear flows, and vortex flow. His awards include the ASME Fluids Engineering Award (1993) and the Alexander von Humboldt Senior Distinguished U.S. Scientist award. He is a fellow of the ASME and associate fellow of the AIAA. Dr. Arndt received his BCE degree from the City College of New York and his SM and PhD degrees from the Massachusetts Institute of Technology.

James P. Brooks is director of Business Development for Litton/Ingalls Shipbuilding and is responsible for directing Ingalls marketing activities and bid and proposal efforts. He is also responsible for developing and implementing the Ingalls Strategic Plan and actively participates in the Ingalls internal research and development program. His background is in ship technology development and application and in electrical engineering. Mr. Brooks has been with Ingalls since 1982. He held positions in the Ingalls Aegis shipbuilding engineering and program office organizations in Mississippi and in Washington, D.C. He received two individual awards for excellence in shipbuilding during this time and holds one ship design patent. Previously he was an employee of the Space Physics Research Laboratory at the University of Michigan. Mr. Brooks received a BSEE from the University of Michigan in 1982. He is a member of the American Society of Naval Engineers, the Surface Navy Association, and the Naval Studies Board.

Daniel S. Cieslowski has been a private consultant since retiring from the Naval Surface Warfare Center, Carderock Division, two and a half years ago. He earned his BME at Catholic University and has also taken postgraduate classes at American University, George Washington University, and Catholic University in engineering and management. He began his federal career at the Carderock Division as a naval architect, worked as the hydrofoil coordinator for hydromechanics, and then became branch head, Special Systems Branch. Mr. Cieslowski progressed to assistant to the department head for Exploratory Development and then to head of the Ship Dynamics Division. He retired as assistant to the directorate head for Operations at Carderock. Mr. Cieslowski's regular duties and areas of responsibility included seakeeping, maneuvering, stability, and control of naval surface ships, submarines, and craft. His programs addressed characterization of the ocean environment, dynamic evaluation of advanced ship types, design and evaluation of submarine control systems, and vehicle/control system integration. His technical efforts ranged from basic research into vehicle dynamic behavior to the design of trainers for full-scale implementation of control concepts. He was responsible for implementing Navy policies and for planning technical and managerial initiatives in his Division. He has served with ASME, the American Society of Naval Engineers, and the Society of Naval Architects and Marine Engineers and is a member of Tau Beta Pi.

Donald M. Dix is a consultant to Center for Naval Analyses and the Institute for Defense Analyses. Previously he held positions at the Office of the Director of Defense Research and Engineering, Department of Defense, first as staff specialist for Propulsion (1981-1990) and then as director (until 1999). He has received the Airbreathing Propulsion Award from the AIAA, the Exceptional Civilian Service Award from the Office of the Secretary of Defense, and an OSD award for Excellence. Dr. Dix received his SB, SM, and ScD in mechanical engineering from the Massachusetts Institute of Technology.

Thomas T. Huang is principal scientist-hydrodynamics (1998-present) for Newport News Shipbuilding and Drydock Company. His professional interests are in ship hydrodynamic design, computational and experimental fluid engineering, viscous flow, cavitation, and hydroacoustics. Dr. Huang received his BS in agricultural engineering from the National Taiwan University, his MS in mechanics and hydraulics from the State University of Iowa, and his PhD in applied physics from the Catholic University of America. Dr. Huang has more than 35 years experience in various aspects of hydrodynamics, beginning with his work at the David Taylor Model Basin in 1968. He served as senior research

scientist-hydrodynamics and chief hydrodynamist at NSWCCD (1990-1998) and as member and chairman of the Cavitation Committee of the International Towing Tank Conference (1980-1990). He has developed technology to improve the hydromechanical performance of naval ships and submarines. He received the Navy's David W. Taylor Award and is a fellow of the American Society of Mechanical Engineers.

Fazle Hussain is Cullen Distinguished Professor at the University of Houston, Department of Mechanical Engineering, and is director of the University's Institute for Fluid Dynamics and Turbulence. His research is in turbulence, vortex dynamics, hydrodynamic stability, and measurement techniques. He is a fellow of the APS, a fellow of the ASME, and an associate fellow of the AIAA. He has received the Fluid Dynamics Prize from the APS and the Freeman Scholar (biennial) award of ASME and was inducted into the Johns Hopkins Society of Scholars and the Third World Academy of Sciences, Trieste.

Antony Jameson is Thomas V. Jones Professor of Aeronautics and Astronautics at Stanford University. His research interests are in computational fluid dynamics, optimal design and control, and shock waves, and he is the author of software that is widely used in the aeronautical industry. He received the NASA medal for Exceptional Scientific Achievement, the AIAA Fluid Dynamics Award, and the Spirit of St. Louis Award from the ASME. Dr. Jameson received his MA and PhD from Cambridge University, England. He is a foreign member of the National Academy of Engineering, a fellow of the Royal Society, a fellow of the AIAA, and an honorary fellow of Trinity Hall, Cambridge.

Reuven Leopold is president and chief executive officer of SYNTEK Technologies, Inc. His primary expertise is in ship design and construction. He received his BSc, MSc, MME, and PhD from the Massachusetts Institute of Technology and his MBA from George Washington University. Dr. Leopold has served on several industrial advisory boards, and his government service includes having been the technical director of ship design for the U.S. Navy during the 1970s. He has also served as a member of the CNO Executive Panel and the Defense Science Board and as a committee member for various Naval Studies Board efforts. His awards include the Albert A. Michelson Award from the U.S. Navy League, the Harold E. Saunders Award from the American Society of Naval Engineers, and the U.S. Navy's Superior Civilian Service Award. He is a fellow of the Society of Naval Architects and Marine Engineers and a member of the Royal Academy of Engineering.

RADM Malcolm MacKinnon III, USN (retired), is president of MSCL, Inc. His primary interest is in ship design and construction. During his 35-year career in the Navy, he was responsible for the design of two new classes of nuclear submarines. Since then, he has turned to commercial shipbuilding and design, emphasizing the introduction of foreign technology and practices into U.S. shipyards to increase their competitiveness and productivity. He has studied advanced technologies for hull form, composite materials, coatings to reduce friction and marine fouling, electrical power generation, and waste remediation and management for application to new ship designs. He is also active in ocean engineering, especially deep ocean search and recovery, marine salvage, and unmanned undersea vehicles. He is a member of the National Academy of Engineering.

W. Kendall Melville is professor of oceanography and chair of the Graduate Department at the Scripps Institution of Oceanography, University of California at San Diego. He received his BS, BE, and MEngSc degrees from the University of Sydney and his PhD from the University of Southampton, England, where he was a Hawker Siddeley fellow. He came to the United States to the Institute of Geophysics and Planetary Physics at the Scripps Institution in 1977, spent 11 years as a professor at the Massachusetts Institute of Technology (1980-1991), and returned to Scripps in 1992. His research interests are in nonlinear surface and internal waves, air-sea interaction, surface wave breaking, and acoustic, optical, and microwave remote sensing. In 1986 he was awarded a John Simon Guggenheim

Memorial Fellowship for the study of ocean waves. Dr. Melville has served on various committees to review government laboratories and research programs.

J. Nicholas Newman is professor emeritus of naval architecture, Department of Ocean Engineering, at the Massachusetts Institute of Technology. His expertise is in marine hydrodynamics, especially theoretical and computational studies applicable to ship hydrodynamics, and he authored the textbook *Marine Hydrodynamics*. Dr. Newman received his BS and MS in naval architecture and marine engineering from the Massachusetts Institute of Technology and also his DSc in theoretical hydrodynamics. His awards include the Royal Institution of Naval Architects Bronze Medal and the Society of Naval Architects and Marine Engineers Davidson Medal. Dr. Newman was the Georg Weinblum Memorial Lecturer (1988-1989) and is a foreign member of the Norwegian Academy of Science and Letters. He is a fellow of the Society of Naval Architects and Marine Engineers, a member of the American Association for the Advancement of Science, and a member of the National Academy of Engineering.

J. Randolph Paulling is professor emeritus of naval architecture, University of California at Berkeley. Previously, he served as chairman of the department and as chairman of the faculty at the College of Engineering. He is a member of the editorial committee of the *Journal of Ship Research* and a member of the U.S. Coast Guard Scientific Advisory Committee. His awards include the Society of Naval Architects and Marine Engineers David W. Taylor Gold Medal for notable achievement in naval architecture, and he was named as one of four U.S. Eminent Ocean Engineers by the American Society of Civil Engineers and the Japan Society for the Promotion of Science. He is a fellow of the Society of Naval Architects and Marine Engineers (vice president from 1985 to 1988), a fellow of the Royal Institution of Naval Architects, and a member of the National Academy of Engineering.

Maurice M. Sevik retired from the Naval Surface Warfare Center, Carderock Division, in January 1999 and currently works there as a consultant for the University of Washington. His area of expertise is in quiet navy ships and submarines and in hydrodynamic phenomena yielding vibration and noise. Dr. Sevik received his BS in mechanical engineering from Robert College (Istanbul), his DIC in aeronautics from the Imperial College of Science and Technology (London), and his PhD in engineering mechanics from Pennsylvania State University. At Pennsylvania State University he became a member of the graduate faculty, professor of aerospace engineering, and director of the Garfield Thomas water tunnel. He was named overseas fellow, Churchill College, University of Cambridge, England. In 1972, he became associate technical director and head of the Ship Acoustics Department, David Taylor Model Basin, where he developed stealth technologies for Navy ships, especially submarines, established a new acoustic range in Alaska, implemented major upgrades of acoustic facilities on the East and West Coasts in support of submarine stealth, and developed a major research and test facility at Lake Pend Oreille, Idaho. His awards include the American Society of Naval Engineers Gold Medal, the ONR Robert Conrad Dexter Award, the ASME Per Bruel Gold Medal for Noise Control and Acoustics, the Charles B. Martell Award from the National Security Industrial Association, l'Ordre du Mérite from the Government of France, the Presidential Rank award, and the Navy's Meritorious and Superior Civilian Service awards. He was named Distinguished Alumnus by the Pennsylvania chapter of the Acoustical Society of America, and the Acoustic Data Analysis Center building at Carderock bears his name. He is a fellow of the American Society of Mechanical Engineers and the Acoustical Society of America and is a member of the National Academy of Engineering.

Robert E. Whitehead retired from federal service in 1997. He began his career in 1971 with the Navy as a research engineer in the Aviation Department of the David Taylor Naval Ship R&D Center at Carderock. He transferred to the Office of Naval Research in 1976 and held a number of positions before becoming director of the Mechanics Division from 1986 until 1989. He then transferred to

NASA headquarters, eventually becoming the associate administrator for Aeronautics and Space Transportation Technology in 1997. In this position, he led a Research and Technology Enterprise of over 6,000 civil service employees and a similar number of contractors at four research centers with an annual budget of approximately \$1.5 billion. During his federal service career, he was awarded both the Presidential Meritorious and Distinguished Executive awards, and at NASA he was awarded the Distinguished Service Medal. He is a fellow of the American Institute of Aeronautics and Astronautics. Dr. Whitehead earned his BS, MS, and PhD in engineering mechanics from Virginia Polytechnic Institute.

D

Acronyms and Abbreviations

ARL/PSU	Applied Research Laboratory, Pennsylvania State University
CFD	computational fluid dynamics
CHA	computational hydroacoustics
CWD	computational wave dynamics
DARPA	Defense Advanced Research Projects Agency
DD-21	next-generation surface combatant
IR&D	independent research and development
JASONS	a self-nominating academic society that conducts technical studies for the Department of Defense (meets in <u>J</u> uly, <u>A</u> ugust, <u>S</u> eptember, and <u>O</u> ctober and produces a report in <u>N</u> ovember).
LES	large eddy simulation
LHA	amphibious assault ship (general-purpose)
LSV	Large Scale Vehicle
MARAD	Maritime Administration (U.S.)
MARIN	Maritime Research Institute of the Netherlands
MEMS	microelectromechanical systems
MRTFB	Major Range and Test Facility Base

NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NRC	National Research Council
NRL	Naval Research Laboratory
NSF	National Science Foundation
NSSN	new attack submarine (now in the Virginia class)
NSWC	Naval Surface Warfare Center
NSWCCD	Naval Surface Warfare Center, Carderock Division
NUWC	Naval Undersea Warfare Center
ONR	Office of Naval Research
OSD	Office of the Secretary of Defense
PIV	particle image velocimetry
RDT&E	research, development, testing, and evaluation
R&D	research and development
R&M	repair and maintenance
SCN	ship construction, Navy
SNAME	Society of Naval Architects and Marine Engineers
SSN	nuclear-powered submarine
SSPA	Swedish Model Basin in Gothenburg
S&T	science and technology
SWATH	Small Waterplane Area Twin Hull
TAGOS 19	an ocean surveillance (SWATH-type) ship
URANS	unsteady Reynolds-averaged Navier-Stokes (equations)



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