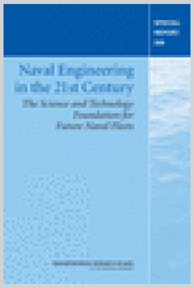

Naval Engineering in the 21st Century: The Science and Technology Foundation for Future Naval Fleets -- Special Report 306

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SPECIAL REPORT 306

Naval Engineering in the 21st Century

The Science and Technology Foundation for Future Naval Fleets

Committee on Naval Engineering
in the 21st Century

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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This report has been reviewed by a group other than the authors according to the procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Preface

Naval engineering is the field of study and expertise that concerns the design, construction, operation, and maintenance of naval ships. The Office of Naval Research (ONR) of the U.S. Department of the Navy sponsors basic and applied research in the scientific and technical fields that support naval engineering as well as education programs to ensure the supply of researchers and engineers in these fields. In 2001, ONR designated naval engineering as a National Naval Responsibility (NNR), one of four technical areas that ONR has so designated. ONR committed to investing in basic and early applied research in the areas of ship design tools, ship structural materials, hydromechanics, advanced hull designs, ship propulsion, ship automation, and ship integration; conducting field experiments that integrate technologies into innovative ship concepts; and investing in students and research facilities in these areas. In addition, ONR stated that it would examine the health of the national science and technology community supporting naval engineering. The purpose of the initiative is to ensure that ONR is able to sustain research in the United States on long-term problems of importance to the Navy; sustain the supply of researchers, engineers, and faculty; and provide superior science and technology in naval architecture and marine engineering. Assigning the NNR designation indicated that (*a*) the listed activities deserve special priority in planning and budgeting at ONR because the identified scientific and technical areas are critical to the Navy and lack support from other sources and (*b*) management of these activities must be coordinated with the stated objective in mind.

This study originated in discussions at meetings of the Marine Board, a subunit of the Transportation Research Board (TRB) of the National Academies. These discussions highlighted the central role of ONR in sustaining research and education in naval engineering and identified the need to assess ONR's effectiveness in fulfilling this role. As a result, in 2009 ONR asked the National Research Council (NRC) to conduct a study to evaluate the state of basic and early applied research in naval engineering and related disciplines in the United States and to review the status of ONR's efforts, through the National Naval Responsibility for Naval Engineering (NNR-NE) initiative, to ensure a healthy research and educational enterprise that meets the future technology needs of the Navy. TRB formed the Committee on Naval Engineering in the 21st Century to respond to this request. The committee included members with experience in research in the fields that support naval engineering and in ship design and construction and included three current or past members of the Marine Board.

The committee relied on four sources of information in preparing its report. First, it reviewed past assessments of the state of the scientific and technical fields that support naval engineering by the Navy, NRC committees, and professional societies. Second, it received from ONR lists of the basic and applied research and educational projects making up the NNR-NE portfolio and data on papers published and graduate students supported through ONR research grants in the NNR-NE technical areas. These data indicate the scope and direction of the initiative and the institutions and researchers that participate.

Third, the committee commissioned nine papers addressing aspects of its task. The backgrounds of the authors include scientific research, command and management experience in the Naval Sea Systems Command (NAVSEA) and in ONR, technology policy, naval history, and private-sector management and technical experience in naval and commercial ship design and construction. Appendix B gives the authors.

Finally, the committee held three public information-gathering meetings organized as workshops. The committee asked the speakers and discussants to address specific questions concerning innovation, the state of research and education, and the role of ONR in naval engineering. Participants included representatives from each of the groups involved in planning, conducting, and applying research in fields related to naval engineering: ONR and other research sponsors; researchers from universities, the Navy laboratories, and industry; educators; NAVSEA; and private-sector shipbuilders and designers. Appendix A lists the workshop participants and presentation topics. The committee drew on the information and advice it received in the workshops and papers in reaching its conclusions.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that assist the authors and 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 following individuals participated in the review of this report: Michael S. Bruno, Stevens Institute of Technology, Hoboken, New Jersey; Charbel Farhat, Stanford University, Stanford, California; Robert E. Hebner, Jr., University of Texas at Austin; Roy S. Kalawsky, Loughborough University, Loughborough, United Kingdom; James L. Kirtley, Jr., Massachusetts Institute of Technology, Cambridge; William B. Morgan, Naval Surface Warfare Center (retired), Rockville, Maryland; Richard W. Thorpe, Herbert Engineering Corporation, Annapolis, Maryland; and Kirsi K. Tikka, American Bureau of Shipping, New York.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the committee's conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by George W. Crabtree, Argonne National Laboratory, Argonne, Illinois, and by C. Michael Walton, University of Texas at Austin. Appointed by NRC, they were responsible for making certain that an independent examination of the report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Joseph R. Morris managed the study under the supervision of Stephen R. Godwin, Director, Studies and Special Programs. Pete Johnson, a consultant to TRB, provided important support to the committee, and Beverly Huey of TRB assisted in several aspects of the study. The report was drafted by members of the committee and by the TRB staff under the guidance of the committee. Suzanne Schneider, Associate Executive

Director of TRB, managed the report review process. Norman Solomon edited the report; Janet M. McNaughton, Senior Editor, handled the editorial production; Juanita Green, Production Manager, coordinated the design, typesetting, and printing; and Jennifer J. Weeks, Editorial Services Specialist, prepared the prepublication manuscript and background papers for web posting, all under the supervision of Javy Awan, Director of Publications. Claudia Sauls assisted with manuscript preparation, data tabulations, and meeting arrangements.

Contents

Summary

The Office of Naval Research (ONR) asked the National Research Council (NRC) to examine the state of basic and applied research in the scientific fields that support naval engineering and to advise it on whether ONR activities, under its National Naval Responsibility for Naval Engineering (NNR-NE) initiative, have been effective in sustaining these fields. The committee's conclusions and recommendations are in five areas: the value of the NNR-NE, the state of science and technology supporting naval engineering, the wholeness of the NNR-NE research portfolio, opportunities for enhancement of research and education, and the effectiveness of the NNR-NE initiative. The principal conclusions below are in bold type. Recommendations are addressed to the administrators of the NNR-NE initiative and of ONR. Recommendations that concern research opportunities could be acted on within the present structure of the initiative. Recommendations for changes in management processes would require action by senior ONR administrators.

NEED FOR AND VALUE OF NNR-NE

Need for Navy Support

Navy support is necessary for basic and early applied research in fields that are critical to naval engineering and lack other sources of support, that have a long-term horizon, and that have potential for discoveries of broad application leading to advances in naval capabilities. Technological progress is essential to security to ensure that naval superiority is maintained as the operating environment, missions, and resources available to the Navy change in the future. This support is valuable not only because it is necessary in meeting defense requirements but also because U.S. Department of Defense research funding historically has yielded benefits beyond national defense and because the department is a primary funder of research and education in a number of engineering disciplines of importance to the U.S. economy. Without Navy support, the critical mass of expertise and research talent in these fields would not be maintained, and the capability to innovate in naval engineering would be lost.

Value of NNR-NE

NNR-NE, as defined in the 2001 ONR memorandum establishing it and the ONR instructions defining the NNRs, is a useful means of organizing support of basic and applied research in the scientific and technical fields that underlie naval engineering. Assigning the NNR designation established Navy policy that the identified activities are deserving of special consideration in planning and budgeting at ONR and are to be managed in coordination so as to sustain U.S. research capability in problems important to the Navy, maintain the supply of scientists and engineers in disciplines of unique Navy importance, and ensure that ONR can continue to provide the science and technology necessary for naval superiority.

The need for NNR designation is particularly great in the case of naval engineering, an essentially integrative activity that must apply scientific knowledge from an expansive array of disciplines to solve complex problems of naval ship design. The attention to long-term planning and coordination of research that the NNR process calls for is critical for producing innovation in naval engineering.

STATE OF SCIENCE AND TECHNOLOGY SUPPORTING NAVAL ENGINEERING

The committee examined the state of research, education, and infrastructure in the six fields supporting naval engineering identified by ONR as within the scope of NNR-NE:

- Ship design tools;
- Structural systems;

- Hydromechanics and hull design;
- Propulsors;
- Automation, control, and system integration; and
- Platform power and energy.

Chapter 5 summarizes the committee's conclusions concerning the individual fields. General conclusions are presented below, as well as a recommendation for a process for ONR to follow in monitoring the health of these fields.

State of Research

The task statement for this study indicates that ONR seeks to "ensure a healthy research and educational enterprise" supporting naval engineering. A healthy research field is one that is productive in advancing knowledge, has linkages to engineering practice as evidenced by transitions of discoveries to applications and by communication between researchers and practitioners, and has positive prospects as evidenced by retention of researchers and attraction of new researchers and resources.

Some of the fields within the NNR-NE derive strength from the breadth of related applications. These fields benefit from diversity of funding sources and opportunities for cross-fertilization among communities of researchers working under different sponsorship. For example, vibrant research communities are devoted to computational fluid dynamics and to structural systems. In these fields, the tasks for the NNR-NE initiative are to ensure that the Navy takes advantage of the pool of researchers that could contribute to solving its problems and to fund research on specific problems relevant only to Navy applications. In other NNR-NE fields or subfields (e.g., propulsors and naval hydrodynamics), ONR and other Navy agencies are nearly the only sources of support. ONR has great responsibility for sustaining education and the institutional infrastructure in these fields.

> **Recommendation 1:** To fulfill its obligation under the NNR-NE to sustain U.S. research capability to work on problems important to the Navy, ONR should carry out regular systematic assessments of the state of health of each of the research fields supporting naval engineering in the United States.

The assessments should examine the objectives and progress of research supported by all government and private funders. As part of its monitoring of the health of these fields, ONR should evaluate worldwide innovation in naval engineering practice and identify the research outputs that have been the sources of the enabling technologies.

State of Education

The education establishment that conducts research and trains future researchers in the NNR-NE fields draws strength from the diversity of the disciplines engaged. However, research centers and departments concentrating on certain specialized fields critical to naval engineering and deriving a large share of their support from ONR (including research centers and departments that perform research in hydrodynamics and in naval ship design methods) may be vulnerable. A decline in research support would cause these departments to diminish, research capabilities to be lost, and the supply of researchers to be interrupted.

> **Recommendation 2:** In carrying out its responsibility under the NNR-NE to sustain the research and graduate infrastructure supporting naval engineering and to ensure the supply of future researchers, ONR should make a special effort to encourage multidisciplinary graduate programs focused on naval engineering that train future researchers and professionals.

State of Infrastructure

Institutional infrastructure is the organizational framework of research: schools; university, government, and industry research laboratories; grant-making organizations; and professional societies. Physical infrastructure is the facilities required to carry out research, for example, towing tanks, wave basins, and cavitation flow tunnels.

The institutions participating in naval engineering science and technology are the Navy, the shipbuilding and ship design industries, commercial ship operators, and research universities and other research organizations. U.S. industry investment in offshore technology is strong, and industry demand for marine professionals is vital in supporting the maritime-related university infrastructure. U.S. universities are a rich source of expertise that potentially is applicable to Navy problems but is not fully utilized by the Navy now. The U.S. government is overwhelmingly the major supporter of relevant research. Within the U.S. government, the Navy is the largest supporter, and within the Navy, ONR.

The committee collected limited data on physical research infrastructure from ONR, Navy laboratories, and naval engineering researchers. No obvious shortfalls were identified. Maintaining and funding test facilities are challenges. Facilities rely heavily on use fees collected from users conducting government-sponsored research; therefore, if research funding is interrupted, survival of facilities is jeopardized. The committee calls the attention of ONR to the 2000 report of the NRC Committee for Naval Hydromechanics Science and Technology, which noted that these facilities require ongoing investment in updated instrumentation and strong technical support staffs to produce cutting-edge research.

WHOLENESS OF THE NNR-NE PORTFOLIO

The task statement directs the committee to "assess the wholeness of the program" and to "assess whether [the six technical areas] adequately define the scope of NNR-NE."

Overall Portfolio

Relation of the Portfolio to Needs and Objectives

The wholeness of the NNR-NE portfolio can be judged only by comparing its objectives and accomplishments with the Navy's priorities for innovation in naval engineering. Priorities should be determined through regular communication with ship designers, fleet strategic planners, and researchers in the fields allied with naval engineering and should be specified in a plan. Planning is necessary in managing an applied research program and is not inconsistent with the spirit of basic research. The committee is not aware of a plan for guiding basic and early applied research in naval engineering–related fields that is specific enough to fulfill this need.

To ensure the wholeness of the NNR-NE portfolio, identification of the implications of U.S. Department of Defense technology needs for basic and applied research priorities by ONR will be necessary. A clear correlation between needs and research emphasis was not always evident to the committee in its examination of the NNR-NE portfolio and its review of the research needs implications of the Navy's operational challenges.

Definition of Technical Areas Within NNR-NE

Advances in each of the six technical areas identified by ONR as within the scope of NNR-NE could contribute to innovation in ship design. Each of the fields, if broadly defined, receives support from sources other than the Navy and has application beyond naval engineering, but the need to maintain expertise in the problems of unique importance to naval engineering justifies including each within NNR-NE.

The major gap in the present definition is inadequate acknowledgment of the need for basic and early applied research in support of the integrative function that is central to the practice of naval engineering. The present portfolio in automation, control, and system integration does not appear to fulfill this need, and ONR needs a new vision to guide research in these areas.

> **Recommendation 3:** ONR should retain the six fields in the definition of the basic and applied research areas within NNR-NE. The definition should state that all ONR basic and early applied research in these fields is to be coordinated to meet the goals of the NNR-NE. In particular, basic and early applied research in platform power and energy should be retained in the definition regardless of where this activity is housed in ONR. In addition, the definition should explicitly identify multidisciplinary systems engineering as an area of basic and early applied research within NNR-NE.
>
> **Recommendation 4:** The Navy should dedicate an important share of its resources for naval engineering science and technology to problems whose solutions are expected to have broad applicability to a range of possible future ship programs.

Research Portfolio in Each NNR-NE Technical Field

The committee considered three aspects of the research projects in each field: intellectual quality, mission alignment, and management commitment.

The research portfolios in some NNR-NE fields (including power and energy and structural systems) appear to be of high intellectual quality, organized around well-defined objectives, demonstrating progress, aligned with potential applications, and adequately supported. For other fields (including automation, control, and system integration and ship design tools), the objectives are not evident and the project portfolios appear to lack cohesion or to be too narrowly focused. The problems in the less strong portfolios may be traceable to the extent and quality of input from users and the research community in the articulation of research needs and the evaluation of research products.

The conclusions of the committee concerning the research portfolio in each of the NNR-NE fields are presented in Chapter 5. Recommendations concerning two elements of the portfolio are as follows.

> **Recommendation 5:** ONR should view total ship systems as a legitimate topic of basic and early applied research, and all such research at ONR should be coordinated through the NNR-NE framework.
>
> **Recommendation 6:** To ensure continuity of component and subsystem technology, the Navy should pursue research and development for power and energy systems in partnership with U.S. industry. It is equally important to pay due attention to integration of the power system with the total ship system and to transition of the technology rapidly and effectively to the ship planners. The transition process should be initiated in the early conceptual design stages.

OPPORTUNITIES TO ENHANCE RESEARCH AND EDUCATION

Opportunities exist for offering significantly improved capabilities to the fleet through basic and applied research in the scientific and technical fields supporting naval engineering. Opportunities presented by new technology and demands for technology arising from Navy requirements, as well as opportunities for enhancing ONR education programs, are identified in Chapter 5.

> **Recommendation 7:** In planning the NNR-NE research portfolio, ONR should search for research directions from both (*a*) emerging

scientific and technological developments that hold promise for providing new capabilities and (*b*) gaps in fundamental knowledge that are hindering fulfillment of needs identified by the operating Navy. The search should be systematized, adequately funded, measured, and incentivized and should be included as part of the organization's and its managers' performance evaluation processes.

Recommendation 8: ONR should embrace its role as the lead agency for the Navy in promoting primary and secondary science, technology, engineering, and mathematics (STEM) education and adequately fund, measure, incentivize, and manage STEM activities as part of its portfolio, in cooperation with the Naval Sea Systems Command (NAVSEA), the professional societies, and industry.

NNR-NE EFFECTIVENESS

The task statement directs the committee to "assess the NNR-NE's progress in the ability to: (l) provide and sustain robust research expertise in the United States working on long-term problems of importance to the Department of the Navy; (2) ensure that an adequate pipeline of new researchers, engineers, and faculty continues; and (3) ensure that ONR can continue to provide superior S&T [science and technology] in naval architecture and marine engineering."

Overall Effectiveness

The conclusions listed below concern the effectiveness of the NNR-NE and factors that influence its effectiveness. Chapter 5 explains the basis for each conclusion.

- **NNR-NE meets a Navy need but requires planning and stronger links to users and researchers.**
- **NNR-NE has not yet gained recognition within or outside ONR as the focus of naval engineering research.**
- **ONR does not appear to have conducted the reporting required by the memorandum establishing NNR-NE.**
- **The role of NNR-NE in the *Naval S&T Strategic Plan* has not been clearly defined.**

- **ONR has not defined the practical administrative significance of NNR designation.**
- **Some prescribed NNR-NE activities may not have been undertaken.**
- **The scope of NNR-NE responsibilities concerning related research conducted by units other than the Ship Systems and Engineering Research Division and concerning educational activities lacks definition.**

Recommendation 9: ONR should bring NNR-NE in line with the structure of the initiative as envisioned when it was established by taking the following actions:

- ONR management should ensure that the elements and objectives of NNR-NE are communicated to researchers, program officers, and research product users and that ONR managers and grant applicants justify new activities within the scope of the NNR-NE by showing how they will contribute to the initiative's objectives.
- ONR should develop an enterprisewide information system that will make information on NNR-NE projects available to proposers and to ONR's clients.
- ONR should use the information system as a management tool in assessing NNR-NE progress, tracking funding allocation trends, benchmarking performance, and communicating NNR-NE achievements.
- ONR should prepare an annual report that compares accomplishments with the objectives of the NNR-NE.
- In revisions of the *Naval S&T Strategic Plan,* ONR should delineate the expected contributions of the NNR-NE to the plan.
- To fulfill the requirement of the 2001 memorandum for creation of consortia to foster naval engineering science and technology, ONR should consider adoption of the alternative organizational models for cooperative research proposed by the 2002 NRC Committee on Options for Naval Engineering Cooperative Research.
- ONR should revise the definition of NNR-NE, specifying educational responsibilities and requirements for coordination of related research outside the Ship Systems and Engineering Research Division.

Improving NNR-NE Effectiveness

Framework for Research Portfolio Management

High-performance research organizations base portfolio management processes on a series of information search, decision-making, performance, and evaluation tasks (Figure S-1). The assessment, benchmarking, and continuous process improvement activities that align incentives with desired performance are key to portfolio management processes.

ONR collects information on metrics that could be helpful in evaluating progress. However, it is not clear that the metrics are linked to a set of measurable objectives for NNR-NE or whether any NNR-NE goals or objectives are tied to department or agency strategic plans, and the committee was unable to identify an NNR-NE strategic plan. Moreover, the committee could not identify a process by which NNR-NE mission area needs and research strategies are prioritized or a systematic process by which ONR funds are allocated according to needs or prioritized research strategies. Finally, the committee did not find

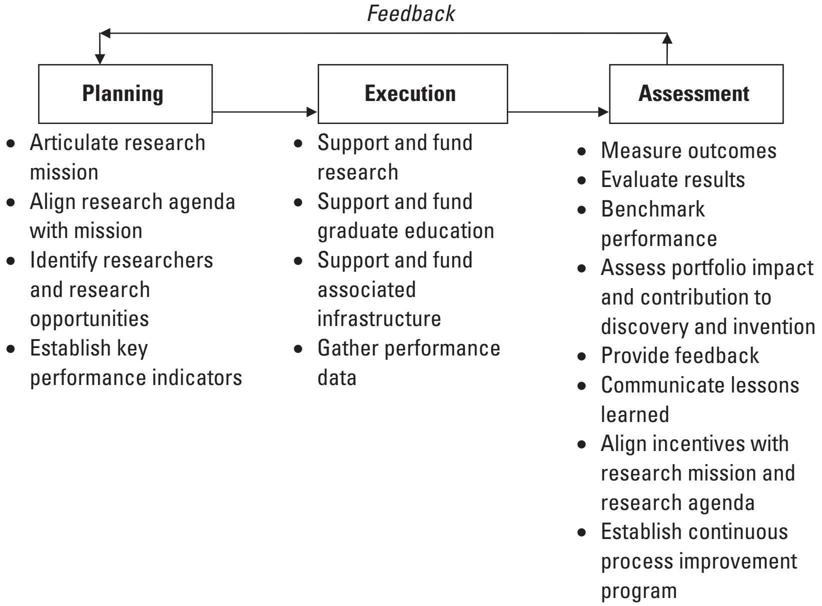

FIGURE S-1 Framework for research portfolio management.

evidence that NNR-NE is measuring or achieving balance in its research portfolio, despite its stated balance goal.

Recommendation 10: ONR should establish an enterprisewide strategic planning and assessment process to develop a strategic plan for NNR-NE, link the plan to goals and objectives, communicate the goals and objectives throughout the naval research community, and evaluate and incentivize NNR-NE performance against the plan. The NNR-NE strategic planning and assessment process should encompass all facets of the NNR-NE mission and should include the following elements:

- A process to articulate and prioritize mission area needs and research priorities on an annual and continuing basis;
- A process for allocation of funds that is aligned with the needs and priorities;
- Metrics for measuring the activities of needs identification, resource allocation, management performance, and continuous process improvement;
- A continuous process improvement activity that utilizes the metrics to assess research portfolio management and to evaluate and report annually on progress;
- An enterprisewide communication system to promulgate lessons learned and best practices; and
- A research portfolio management procedure to guide planning and information collection, administration, and assessment. The procedure should follow recognized standards for research portfolio management, including performance benchmarking. The goal of instituting the procedure should be to establish a culture of continuous process improvement.

Recommendation 11: ONR should identify and use metrics to measure NNR-NE portfolio balance.

Recommendation 12: As input to the identification of research performers, to enhance dissemination of Navy mission and needs, and to improve communication with operational Navy units, in managing the NNR-NE, ONR should utilize mission capability managers responsible for understanding specific Navy missions.

Measuring the Output of NNR-NE

ONR's present metrics for output of its investment in NNR-NE provide useful information. However, they fall short of adequate measures of the benefit of ONR's investment in NNRs.

> **Recommendation 13:** As part of the NNR-NE research portfolio management process, ONR should develop research performance metrics that assess the contribution of its investments to discovery and innovation. Metrics should be inputs to investment decisions in managing the NNR-NE. They also should be used to improve understanding of the importance of ONR naval engineering research. Successes identified through the metrics should be publicized, and research excellence should be incentivized to raise the visibility of research and the standard of quality.
>
> **Recommendation 14:** Because of the complexity of naval engineering science and technology problems, ONR should consider adopting integrative and interdisciplinary performance metrics in NNR-NE (e.g., numbers of interdisciplinary projects and publications and numbers of citations outside the primary disciplines).

Peer Review

Management of the NNR-NE relies primarily on the ONR program officers in selection of projects and project investigators. Review of project proposals and investigators before selection does not involve formal external peer review or other consultative procedures. **External peer review (i.e., review by technical experts from outside ONR) throughout the research project selection process would offer the opportunity to strengthen project selection and to obtain the advice and counsel of technical experts, NAVSEA technical authorities, and industry practitioners who are the ultimate recipients of the developed technology, while maintaining the ONR program officer's independence in making decisions for his or her program.**

> **Recommendation 15:** ONR should establish a process for NNR-NE in which the program officer assembles a small group of Navy laboratory technical experts and NAVSEA technical authorities to assess and rank research proposals. The program officer would be responsible

for considering the recommendations and selecting projects. The midproject external review that ONR already conducts would be carried out by this panel with the addition of external reviewers.

Technology Interpreter

Recommendation 16: ONR should implement the concept of the technology interpreter in the NNR-NE. The task of the technology interpreter would be to assist in the technology transition process. The recommended peer-review panels would implement the technology interpreter concept in the program officer and technical authority communities. Frequent communication between these communities would inform the program officer of technologies that the technical authorities require and inform the technical authorities of new technologies as they emerge and mature. In addition to the review panels, personnel dedicated to improving communications and execution could significantly improve NNR-NE integration with Navy missions and operational requirements.

Maintaining Connections Across the Wider Naval Engineering Community

Maintaining connections across the wider naval ship systems engineering community means bridging the valleys that naturally exist between the naval research, design, manufacturing, and operational communities and the commercial and offshore communities. **Connectivity, communication, and human resource and organizational development are important to the success of the naval engineering enterprise. However, the committee was unable to find evidence that NNR-NE strategic research planning makes use of measures of these dimensions of performance.**

Recommendation 17: To maintain connectivity among the wider naval engineering community, NNR-NE should utilize the concept of technology interpreter. ONR should consider additional connectivity and communication activities, including seminars, scholarly exchanges, and rotation opportunities for NNR-NE program officers such as research sabbaticals.

Recommendation 18: ONR should incorporate human capital and organizational development goals and objectives as explicit responsibilities of NNR-NE.

Integrating Naval Engineering Science and Technology

The committee found examples of interdisciplinary and integrative research in the NNR-NE portfolio. However, these efforts were the outgrowth of initiatives of individual program officers rather than of ONR processes that encouraged interdisciplinary or integrative research.

Recommendation 19: ONR should establish processes that encourage interdisciplinary and integrative research in NNR-NE.

Developing Human Capital and Revitalizing Naval Ship Systems Engineering

Recommendation 20: ONR should reinvigorate its efforts in developing the 21st century naval engineering workforce, including improvement of outreach activities to underrepresented groups. ONR's lead role in STEM primary and secondary education activities should be strengthened and incorporated into its enterprisewide strategic planning processes, and performance metrics for workforce development and STEM achievements should be identified.

1

Introduction

The United States Navy is the world leader in warship capabilities that allow the nation to respond to security threats at sea. A key factor in maintaining naval superiority is a solid science and technology (S&T) foundation supporting innovation in the design, construction, and maintenance of the Navy's ships. The Office of Naval Research (ONR) supports the S&T that will be essential to the fleets of the future.

Naval engineering includes all engineering and sciences as applied in the design, construction, operation, maintenance, and logistical support of surface and subsurface ships, craft, and vehicles used by the Navy. The problems of naval engineering include the architecture and engineering of the mission, platform, and human systems that make up the ship. Naval engineering includes the design of weapons and related combat systems; however, this study's consideration of these systems was limited to their integration into and support by the ship itself.

ONR supports basic and applied research in the scientific and technical fields that sustain innovation in naval engineering. It also supports educational programs to ensure the availability of new researchers entering naval engineering–related fields. ONR defined the scope, focus, and objectives of certain of its naval engineering S&T activities in a 2001 memorandum that designates naval engineering as a national naval responsibility (ONR 2001). ONR at present defines the scope of its National Naval Responsibility for Naval Engineering (NNR-NE) initiative to include five technical fields: structural systems; ship design tools; hydromechanics and hull design; propulsors; and automation, control, and system integration (J. Pazik, presentation to the committee, April 6, 2010). In addition, until 2010, the ONR division responsible for NNR-NE managed a program of basic and applied research projects in platform power and energy, which ONR included in tabulations of NNR-NE projects provided to the committee.

In 2009, ONR asked the National Research Council (NRC) to examine the state of basic and applied research in the scientific and technical fields that support naval engineering and to advise ONR on whether activities under its NNR-NE initiative have been effective in sustaining these fields. ONR also asked NRC to identify opportunities to enhance innovation, research, and graduate education in these fields and to identify areas of scientific research that provide opportunities for fundamental advances in naval ship capabilities. Box 1-1 presents the committee's task statement.

BOX 1-1

Committee on Naval Engineering in the 21st Century: Statement of Task

This study will evaluate the current state of science and technology—specifically, basic and early applied research—activities in naval engineering and closely related disciplines in the United States in the context of research, education (the "pipeline" of future naval researchers, graduate and postdoctoral), and the associated infrastructure. It will assess the robustness of activity, and, if appropriate, identify potential gaps and shortfalls in research and educational (graduate and postdoctoral) programs. As appropriate, the study will provide recommendations for new opportunities to enhance innovation, research, and graduate educational capabilities in basic and applied research.

Ultimately, the goal of this study is to inform the Office of Naval Research (ONR) on the status of its efforts, under the National Naval Responsibility in Naval Engineering (NNR-NE), to ensure a healthy research and educational enterprise that meets the future technology needs necessary to advance the Navy's ability to provide highly capable and affordable sea platforms.

This project will collect, synthesize, and evaluate data regarding seven (7) key university, government, and industry research activities in naval engineering: ship structural materials, design tools, hydromechanics, advanced hull designs, ship propulsion, ship automation, and systems integration. The data collected will be evaluated to assess the wholeness of the program and, as appropriate, identify any key opportunities for the Navy to make fundamental leaps in sea platform capability and affordability. The study will assess whether these seven disciplines adequately define the scope of NNR-NE. It will report on the health of the basic and early applied research, graduate and postgraduate research "pipeline" and the associated infrastructure necessary for a long-term, sustainable portfolio that will provide technology options for future Navy advanced technology development programs and affordable sea platforms.

The study will advise on the ability of the NNR-NE's portfolio of programs to provide steady, long-term support to the Navy unique core disciplines of naval engineering. Recommendations will be provided on the research areas within these disciplines necessary for the Navy to maintain/advance capabilities and affordability of future Navy platforms. It will assess the ability of the NNR-NE to maintain healthy and robust research activities, educational capabilities (graduate and postdoctoral), and the infrastructure that supports both. The study will comment on advances in naval engineering research and research "pipeline" activity since the initiation of the NNR-NE. Specifically, it will assess the NNR-NE's progress in the ability to: (l) provide and sustain robust research expertise in the United States working on long-term problems of importance to the Department of the Navy; (2) ensure that an adequate pipeline of new researchers, engineers, and faculty continues; and (3) ensure that ONR can continue to provide superior S&T in naval architecture and marine engineering.

NRC formed the Committee on Naval Engineering in the 21st Century to respond to ONR's request. This report presents the results of the committee's investigations and analyses.

This chapter introduces naval engineering as a vital technical discipline and research and development enterprise in support of the Navy's overall mission. It provides an overview of ONR's NNR-NE initiative and discusses related activities as well as its connection to the larger ship design, development, and construction industries. The NNR-NE initiative has important connections to two larger endeavors: ONR's overall research program and the nation's overall naval engineering enterprise. This report will point out these connections and describe how ONR can use them to enhance its mission and meet its goals.

NATIONAL NAVAL RESPONSIBILITY FOR NAVAL ENGINEERING

ONR's mission, as defined in federal law, is to "plan, foster, and encourage scientific research in recognition of its paramount importance as related to the maintenance of future naval power, and the preservation of national security" and to "manage the Navy's basic, applied, and advanced research to foster transition from science and technology to higher levels of research, development, test, and evaluation" (ONR 2009, 1).

ONR's Discovery and Invention (D&I) portfolio makes broad investments in basic and applied research, and within this portfolio, ONR has identified four areas as NNRs: ocean acoustics, underwater weaponry, underwater medicine, and naval engineering. These areas were designated because they are essential to innovation in naval capabilities and because no organization other than the Navy will continually support research fulfilling unique Navy needs. ONR is committed to sustaining research investment in these areas (ONR 2009, 26).

Naval engineering was designated an NNR in a 2001 ONR memorandum that specified the purpose of the designation and the activities that were to constitute the NNR-NE (Box 1-2). The memorandum was from F. E. Saalfeld, Executive Director of ONR (the senior civilian manager at ONR), and addressed to the director of ONR's Engineering, Materials, and Physical Sciences Science and Technology Department. ONR was

BOX 1-2

National Naval Responsibility for Naval Engineering

The purpose and actions for execution of the constituent activities of the NNR-NE according to the memorandum "National Naval Program for Naval Engineering" (ONR 2001) are summarized below.

Purpose of defining the NNR-NE: The initiative is to position ONR to take responsibility for

- Sustaining robust research in the United States on long-term problems of importance to the Navy;
- Continuing an adequate pipeline of new researchers, engineers, and faculty; and
- Continuing to provide superior S&T in naval architecture and marine engineering.

Execution: The purpose of the NNR-NE is to be achieved by the following actions:

- ONR is to dedicate the resources necessary for developing innovative shipbuilding concepts. In particular, resources are to be provided for
  - Investing in seven key S&T areas: ship design tools, ship structural materials, hydromechanics, advanced hull designs, ship propulsion, ship automation, and ship integration;
  - Conducting major field experiments that integrate technologies into innovative ship concepts; and
  - Investing in infrastructure such as students, facilities, and equipment.
- ONR is to examine the health of the national S&T community and, to ensure long-term strength in naval engineering, was to issue special broad agency announcements for three purposes:
  - Developing half of the pipeline of future naval researchers required to sustain expertise in naval engineering (estimated as five graduate and five postdoctoral fellowships per year),

(continued on next page)

BOX 1-2 *(continued)*

National Naval Responsibility for Naval Engineering

  - Developing university–industry–laboratory consortia for S&T in naval engineering, and
  - Encouraging industry–university partnerships for career development of future naval engineers.

  [This requirement (Item 4.d in the 2001 memorandum) appears to be a further specification of the infrastructure investments that the preceding bullet point (Item 4.a in the memorandum) calls for.]
- The ONR division responsible for the NNR-NE is to seek the required resources through ONR's Investment Balance Review and other appropriate channels.
- The progress and impact of the efforts supporting NNR-NE are to be reviewed every 5 years by a panel of experts including academic, military, and industry representation.

The ONR instruction stating the policy for designating an S&T initiative as an NNR, issued in 2007 and revised in 2010, also specifies required activities in NNR initiatives (ONR 2010, 3–4). The department responsible for an NNR is to

- Formulate thrust areas within the field to provide S&T products that ensure naval superiority,
- Coordinate the NNR with other efforts including ONR Future Naval Capabilities technology transition initiatives and activities at the Defense Advanced Research Projects Agency,
- Augment basic research with experiments focused on promoting applications and balance theoretical with experimental research,
- Promote knowledge base development and retention through a military officer fellowship program or an entry-level faculty support program,
- Report annually on progress of the NNR, and
- Submit the NNR to review by an independent board at least every 5 years.

already engaged in all or nearly all of the specified activities before the memorandum was issued. Rather than initiating new programs, the memorandum served as a declaration of policy: assigning the NNR designation indicated that (*a*) the listed activities deserve special priority in planning and budgeting at ONR because the identified S&T fields are critical to the Navy and no one else will support them and (*b*) management of these activities must be coordinated with the declared policy objective in mind.

ONR provided the committee with tabulations of the basic and applied research projects supported by ONR grants or contracts and of ONR-supported educational projects that made up the NNR-NE portfolio of activities for the years 2006 to 2009. In these tabulations, ONR categorized research projects into six scientific and technical areas:

- Automation, control, and system integration;
- Ship design tools;
- Hydromechanics and hull design;
- Platform power and energy;
- Propulsors; and
- Structural systems.

In addition to the research projects categorized into these areas, the ONR tabulation of the NNR-NE portfolio includes a number of projects categorized as educational. The educational projects are activities to attract students and train beginning researchers in the fields related to naval engineering.

The committee accepted this tabulation as the definition of the ONR research and educational activities that ONR now includes within the NNR-NE initiative. The committee understands that the six scientific and technical areas are the areas that ONR views as constituting the National Naval Responsibility.

This list of the scientific and technical areas within NNR-NE differs somewhat from the list of seven scientific and technical areas specified in the 2001 memorandum creating the NNR-NE (see Box 1-2). It is the committee's understanding that the change since 2001 has been primarily in the titles given to the areas rather than in the scope of the ONR activities considered to make up the NNR-NE initiative. The most

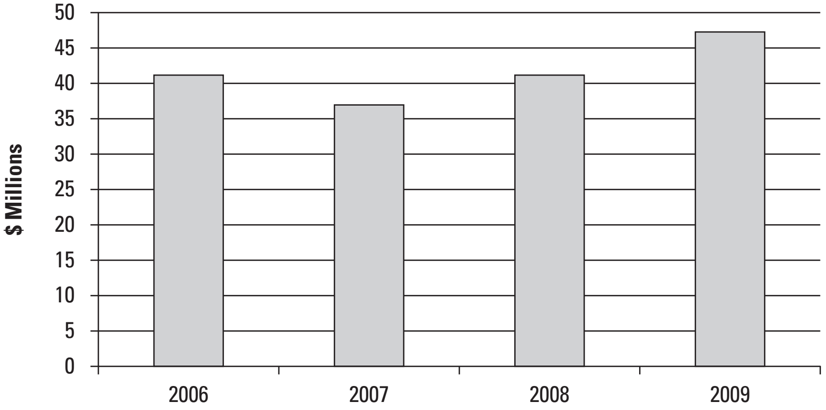

FIGURE 1-1 **ONR spending for naval engineering basic and applied research and education, 2006–2009.** (SOURCE: Tabulations of NNR-NE project data provided by ONR to the committee.)

significant change from the 2001 list of areas is the addition of the platform power and energy category. This addition reflects a substantial but temporary increase in funding in this area, which ONR received after 2001. Presumably, in 2001, projects in power and energy would have been included in the ship propulsion category. Table 4-1 in Chapter 4 compares the 2001 and present lists of scientific and technical areas.

In 2009, the ONR tabulation lists 232 NNR-NE projects under way; they received $47.4 million in ONR funding in that year (Figure 1-1). Most projects are conducted at U.S. universities, with Navy laboratories, private-sector firms, and foreign research institutions also participating (Figure 1-2). Power and energy research projects received the largest share of 2009 funding, followed by projects in hydrodynamics and in structures (Figure 1-3).

NNR-NE IN THE CONTEXT OF ONR's TOTAL RESEARCH PROGRAM

NNR-NE is one element of ONR's overall research and development activities supporting naval engineering. Assessment of the initiative must take into account its relation to the other activities and whether the scope of the initiative is adequately defined. In addition, evaluating whether

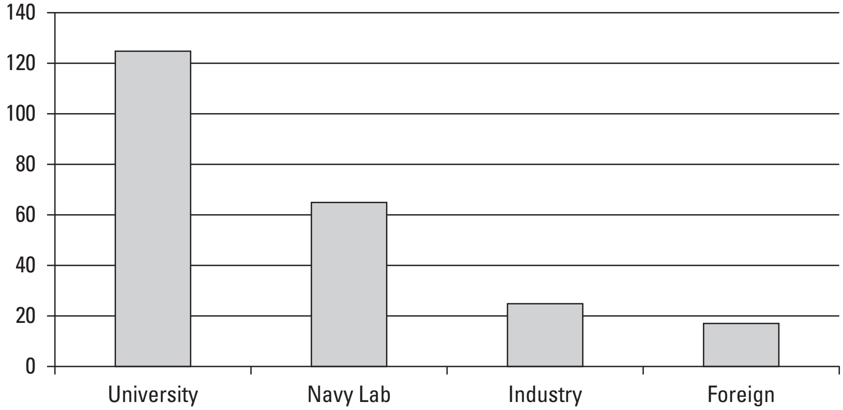

FIGURE 1-2 **Number of active NNR-NE projects by performing sector, FY 2009.** (Source: Tabulations of NNR-NE project data provided by ONR to the committee.)

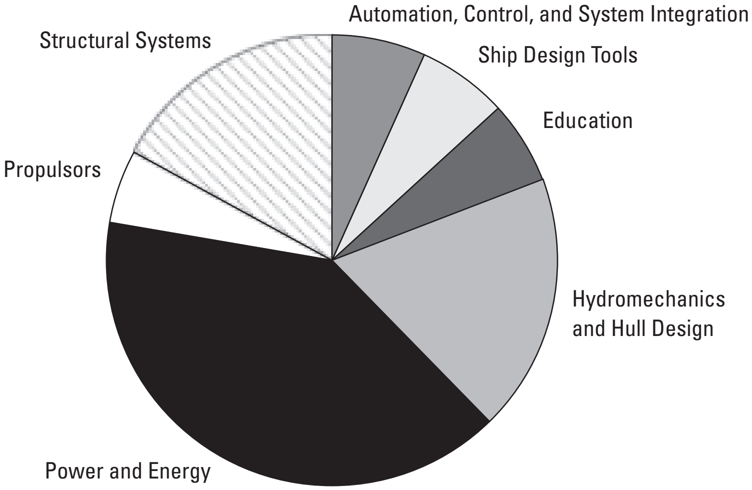

FIGURE 1-3 **Funds committed for NNR-NE projects by field, FY 2009 (total outlays = $47.4 million).** (Source: Tabulations of NNR-NE project data provided by ONR to the committee.)

NNR-NE is capable of satisfying the Navy's needs requires examination of how the initiative is connected to other elements of the innovation process.

ONR's research and development portfolio is organized into three directorates: Research, Innovation, and Transition. This organization seeks to invest in S&T to meet Navy strategic goals through a series of stages, from basic research through development of products that provide new naval capabilities. ONR's *Naval S&T Strategic Plan* describes the D&I research portfolio (the primary activity of the Research Directorate) as follows:

> Discovery and Invention (D&I) consists of Basic Research (Budget Activity (BA) 6.1) and early Applied Research (BA 6.2), and is the seed corn for future naval technologies and systems. The D&I portfolio, by design has a broad focus, and programs are selected based on potential naval relevance and technology opportunity. D&I investments leverage other service, governmental, department, industry, international and general research community investments. The D&I portfolio supports sustained funding of the four National Naval Responsibilities (NNR): Ocean Acoustics, Underwater Weaponry, Naval Engineering and Undersea Medicine. (ONR 2009, 3)

The Innovation Directorate manages ONR's Innovative Naval Prototypes portfolio, projects to develop potentially high-value technologies to a level near the stage of transition to application. The Transition Directorate manages the Future Naval Capabilities portfolio, projects to "mature technology into requirements-driven, transition oriented products" (ONR 2009, 3). These two directorates do not sponsor basic (Budget Activity 1) research.

ONR research and development projects also are organized into six departments according to intended areas of application (see Figure 1-4). NNR-NE is administered by the director of the Ship Systems and Engineering Research Division within the Sea Warfare and Weapons Department.

Research projects in the NNR-NE are exclusively in the D&I portfolio, that is, basic research and early applied research. The definitions that ONR uses for basic and applied research and advanced technology development are shown in Box 1-3. These definitions are used by the Department of Defense in budget formulation and in the department's budget proposals and justifications addressed to Congress for Research,

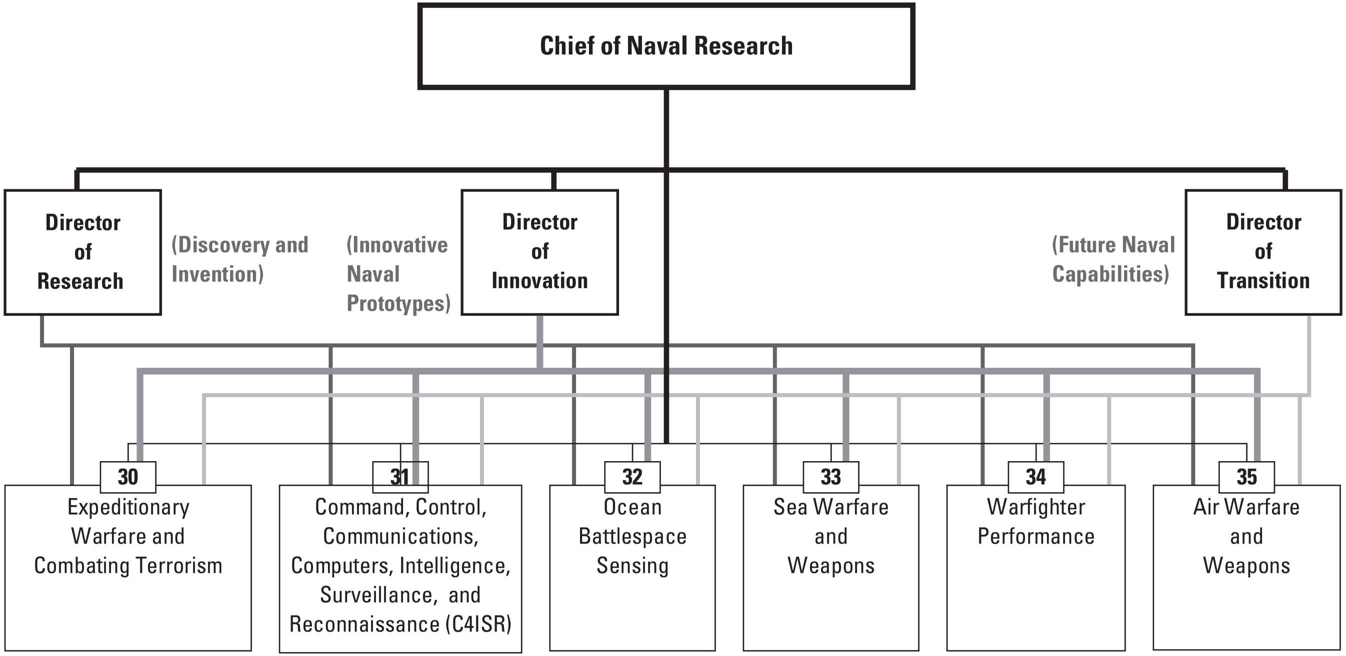

FIGURE 1-4 **ONR S&T directorate organization.** (NNR-NE is managed in the Ship Systems and Engineering Research Division, one of three divisions of the Sea Warfare and Weapons Department.) (SOURCE: J. Pazik, presentation to the committee, April 6, 2010.)

BOX 1-3

Department of Defense Research and Development Budget Activity Definitions

Budget Activity 1, Basic Research: Basic research is systematic study directed toward greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications towards processes or products in mind. It includes all scientific study and experimentation directed toward increasing fundamental knowledge and understanding in those fields of the physical, engineering, environmental, and life sciences related to long-term national security needs. It is farsighted high payoff research that provides the basis for technological progress. . . .

Budget Activity 2, Applied Research: Applied research is systematic study to understand the means to meet a recognized and specific need. It is a systematic expansion and application of knowledge to develop useful materials, devices, and systems or methods. It may be oriented, ultimately, toward the design, development, and improvement of prototypes and new processes to meet general mission area requirements. Applied research may translate promising basic research into solutions for broadly defined military needs, short of system development. The dominant characteristic is that applied research is directed toward general military needs with a view toward developing and evaluating the feasibility and practicality of proposed solutions and determining their parameters, exploration efforts and paper studies of alternative concepts for meeting a mission need. . . .

Budget Activity 3, Advanced Technology Development (ATD): This budget activity includes development of subsystems and components and efforts to integrate subsystems and

> components into system prototypes for field experiments and/or tests in a simulated environment. ATD includes concept and technology demonstrations of components and subsystems or system models. The models may be form, fit and function prototypes or scaled models that serve the same demonstration purpose. The results of this type of effort are proof of technological feasibility and assessment of subsystem and component operability and producibility rather than the development of hardware for service use. Projects in this category have a direct relevance to identified military needs. . . .

Budget Activities 4, 5, 6, and 7 are Advanced Component Development and Prototypes; System Development and Demonstration; Research, Development, Test, and Evaluation Management Support; and Operational System Development, respectively.

Source: DOD 2010.

Development, Test, and Evaluation appropriations. In ONR documents, projects funded as Budget Activity 1 are referred to as basic research, and projects funded as Budget Activity 2 often are referred to as early applied research (to distinguish them from Budget Activity 3 and above projects that might also be characterized as applied research).

Research and development related to naval engineering is conducted under all three directorates. Basic and applied research relevant to naval engineering may also be conducted in divisions other than Ship Systems and Engineering Research (for example, in the Ocean Engineering and Marine Systems Division and in the Naval Materials Division). The 2010 ONR instruction stating the policy for designating new NNRs requires that management of each NNR be coordinated with related Innovative Naval Prototypes and Future Naval Capabilities as well as with relevant research outside ONR (ONR 2010, 3–4). Coordination of relevant D&I research with the NNR in all ONR divisions is not mentioned but is implied.

ONR management seeks to coordinate work in Budget Activities 1, 2, and 3 by vertically integrating management of related programs at all three levels to enhance connectivity and thus allow projects at the three levels to become mutually supporting. The NNR concept is an attempt to establish direction and long-term goals for a group of related basic and applied research programs (Gaffney et al. 1999, 13–15). These arrangements are consistent with the recommendation of the 2005 report of the NRC Committee on Department of Defense Basic Research that the department "should view basic research, applied research, and the other phases of research and development as continuing activities that occur in parallel, with numerous supporting connections among them" (NRC 2005, 5). The intent of such arrangements is that through continuing close contact and interaction among researchers and research managers working on basic research, applied research, and development projects, basic research will be guided in directions with long-term relevance and value. Such coordination is useful not only within ONR and the Navy at large but also with related activities in the entire naval engineering enterprise.

THE NAVAL ENGINEERING ENTERPRISE IN THE UNITED STATES

By definition, naval engineering is multidisciplinary in scope, of broad application, and practiced by a diverse community. It includes engineers engaged in all phases of design, construction, operation, maintenance, and logistical support of naval ships, craft, and vehicles. The practitioners come from various engineering disciplines and have received diverse formal engineering education backgrounds, but they have a common understanding of the unique requirements, characteristics, capabilities, and limitations associated with ships.

The naval engineering enterprise includes all entities that conduct the business of naval ship systems research, development, design, acquisition, construction, operation, maintenance, repair, and disposal. The groups that make up this enterprise in the United States are the Navy commands, private-sector engineering firms, naval shipbuilding and equipment manufacturing industries, universities that conduct research and train engineers and researchers, and private-sector research organizations.

Commercial ship operators and shipbuilders, the recreational yacht and boat industry, and the offshore petroleum industry share technologies with naval engineering. The larger naval engineering enterprise depends on ONR to identify and support research and development leading to improved performance and efficiency. Effective communication between ONR and all elements of the naval engineering enterprise is essential for ensuring that ONR meets the needs of the Navy for innovation.

Of the total technical workforce engaged in the larger enterprise, only a small portion makes up the community conducting the research that is the focus of this study. Scientists and engineers from many disciplines contribute to the knowledge base and bring innovative ideas to naval engineering. The relevant disciplines include aeronautical and aerospace engineering; biosciences; chemical engineering; chemistry; civil engineering; cognitive, neural, and behavioral science; electrical and computer engineering; information sciences; marine engineering; materials science and engineering; mathematics; mechanical engineering; naval architecture; nuclear engineering; ocean engineering; oceanography; operations research; physics; and industrial and systems engineering.

ONR's basic and early applied research programs in support of naval engineering must coordinate the contributions that these disciplines offer by integrating innovations to enable advances in naval capabilities and provide solutions to Navy problems. Figure 1-5 shows the variety of disciplines in which the NNR-NE principal investigators received their graduate training. This diversity indicates that the challenge facing ONR in the NNR-NE initiative is to attract researchers from a broad range of backgrounds to work on a particular set of problems that are critical to the practice of naval engineering.

In addition to ONR, numerous government and private institutions participate in the training of naval engineers and naval engineering researchers and conduct and sponsor basic and applied research and development in support of naval engineering. The following categories of engineering and science schools and research institutions contribute to the naval engineering enterprise:

- Private-sector research and engineering businesses that perform independent or government-sponsored research and development;
- Dedicated U.S. government research and engineering entities;

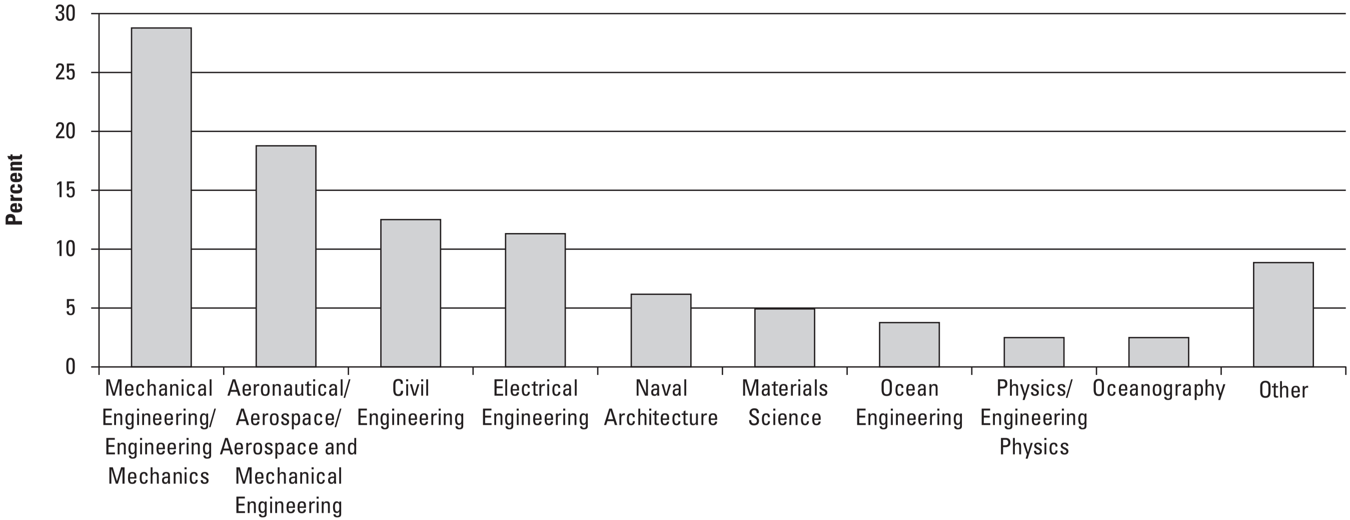

FIGURE 1-5 **Departments in which principal investigators in ONR 2009 NNR-NE projects earned their graduate degrees.** (SOURCE: Project lists provided to the committee by ONR.)

- U.S. universities that have a major program focused on naval engineering and that participate in naval engineering research;
- U.S. universities that typically do not specifically educate for or place students in the naval engineering enterprise but participate in naval engineering research programs;
- U.S. universities focused on education for the maritime sector, including the United States Naval Academy, the Merchant Marine Academy, the Coast Guard Academy, and the Naval Postgraduate School; and
- Foreign research institutions.

ONR supports projects conducted by all of these institutions. In FY 2009 ONR funded research, through its NNR-NE initiative, at 51 U.S. universities, seven Navy and other federal government institutions, 10 private-sector firms, and 13 foreign research institutions. There is little non-ONR funded research at universities on the topics that are funded through the NNR-NE, with the exception of research funded by branches of the Navy. There is also some limited funding of university research by shipyards, major ship operators, and classification societies, but this tends to be more applied research than basic research.

A variety of associated government agencies also participate in the naval engineering enterprise. The Naval Sea Systems Command (NAVSEA) Warfare Centers and Naval Research Laboratory are parts of the naval engineering enterprise that conduct naval engineering–related research. The NAVSEA Warfare Centers include the Naval Surface Warfare Centers (NSWC), which has eight locations, and the Naval Undersea Warfare Center, which has two locations. The Warfare Centers are the Navy's principal research, development, test, and evaluation assessment facilities for surface ship and submarine systems and subsystems. Located at NSWC Carderock is the Center for Innovation in Ship Design (CISD). Its mission is to "ensure the future capability (People, Tools and Knowledge) of the nation to develop innovative ship designs to effectively meet defense needs" (NSWC n.d.). CISD is funded by NAVSEA and by ONR. ONR classifies its CISD contribution as a part of the NNR-NE. A significant part of the total funding through the NNR-NE supports projects within these Navy facilities (especially NSWC Carderock), but this source makes up only a small portion of the total funding of these institutions.

Department of Defense research institutions other than the Navy conduct activities relevant to the objectives of NNR-NE. For example, the Department of Defense funds the Computational Research and Engineering Acquisition Tools and Environments (CREATE) initiative, a 12-year, $360 million program. CREATE is an applied research and development initiative; its purpose is to develop and deploy computational engineering tools for the design of aircraft, ships, and radio-frequency antennas. The National Science Foundation funds basic and applied research in related fields, including fluid dynamics; structural materials; systems engineering, design, and control; and energy and power systems.

Finally, private maritime industries in the United States devote some limited resources to research and development, but for the most part research related to NNR-NE in the maritime industries applicable to Navy ships is funded by the Navy. One example is the National Shipbuilding Research Program (NSRP), which is a collaboration of 11 U.S. shipyards working with government, industry, and academia. NSRP's mission is to manage national shipbuilding and ship repair research and development funding and focus it on technologies that will reduce the cost of warships to the U.S. Navy and other national security customers by leveraging commercial practices and improving the efficiency of the U.S. industry. NSRP also provides a collaborative forum to improve business and acquisition processes. NSRP is sponsored by NAVSEA.

There are examples of industry-led innovations that have served as a route to discovery and invention and subsequently application. In one case, Northrop Grumman Shipbuilding's Gulf Coast Operations led an initiative to bring composites to naval shipbuilding. The company supported initial research and development activities that eventually resulted in partnering with the U.S. Navy on large composite structures. These innovative designs were subsequently installed as a technology demonstration on the USS *Arthur W. Radford* (DD 968) and as a classwide implementation on the LPD 17 and DDG 1000 fleets (Hackett 2010).

In another example, General Dynamics National Steel and Shipbuilding Company (NASSCO) developed a shipbuilding strategy based on licensing proven designs to reduce cost and risk, improve productivity through technology transfer, and leverage purchasing power with large shipyards. This strategy led to a partnership between NASSCO and Daewoo Shipbuilding and Marine Engineering. The partnership is proposing to use the T-AKE dry cargo and ammunition ship as a parent hull for a variety of U.S. Navy needs, including fleet oiler, joint command and control ship, and hospital ship. In this case study, the innovation is not the product but rather the method (B. J. Carter, presentation to the committee, Jan. 13, 2010).

While there is some naval engineering research by the classification societies, it is primarily to support the development of classification rules and construction standards for commercial ships and other marine structures. Other research supported by the maritime industries in the United States has little tangible connection to the naval engineering S&T programs of ONR.

In summary, the ONR NNR-NE initiative must be evaluated within the larger context of the nation's naval engineering enterprise and the ONR's total research effort so that proper emphasis is given to the role of research and development in shaping the naval fleets of the future. The committee's investigations and study results have recognized this and are intended to assist ONR in maintaining a healthy and productive research endeavor to meet mission goals.

REPORT STRUCTURE

Chapter 2 addresses research needs and opportunities in naval engineering. Chapter 3 describes how ONR functions to define goals, determine research agendas, select researchers, measure outcomes of its activities, foster technology transitions, and maintain connections with the wider community in naval engineering. The chapter also identifies alternative models for operating practices. Chapter 4 presents the committee's assessments, based on the analyses in preceding chapters, of the current state of health of the S&T fields that support naval engineering and the contribution of the NNR-NE in sustaining these fields. Chapter 5 summarizes the committee's conclusions and presents recommendations on how ONR can ensure the continued flow of innovations that allow advances in the capabilities of Navy ships.

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Abbreviations

DOD	Department of Defense
NRC	National Research Council
NSWC	Naval Surface Warfare Center, Carderock Division
ONR	Office of Naval Research

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2

Science and Technology Shaping Future Naval Fleets

Scholars have long considered science and technology to be society's window on the future. This theme is evident to the Navy as it depends on the Office of Naval Research (ONR) to fulfill its mission by providing the science, technology, and research necessary to support future naval fleets. To carry out its mission effectively, ONR must not only keep current on scientific advancements, technologies, and innovations but also understand the Navy's future mission needs, threats, and strategies to meet those threats. The committee has reviewed these research opportunities and needs and has identified factors influencing the management and planning process for ONR's National Naval Responsibility for Naval Engineering (NNR-NE) initiative.

ONR uses information about research opportunities and needs for two purposes. The first is to aid in the portfolio management process by communicating needs and expected outcomes to researchers and by balancing user requirements with research opportunities. The second is to aid in planning an effective portfolio with research objectives that are within ONR's naval engineering core disciplines and that are based on future threats and technology trends.

The committee commissioned papers by experts on topics relevant to research needs and opportunities (see Appendix B). In addition, the committee held workshops that included experts in the Navy ship design and construction community as well as prominent researchers in naval engineering who are active in ONR programs (see Appendix A). The commissioned papers and workshop topics included analyses of game-changing technologies in the past with lessons that may be learned from them, reviews of future technologies to enable naval missions to meet potential threats, and investigations of challenges in applying new technologies to warship design and construction.

This chapter addresses both research needs and opportunities. The first section below describes naval engineering research needs dictated by possible future operating environments, missions, and resource constraints. Research opportunities are discussed in the second section, which identifies promising technologies and trends in innovation within the traditional disciplines related to naval engineering as well as other fields of scientific investigation that offer insights and discovery potential. The research opportunities identified are intended as illustrations. The list of opportunities is not systematic or comprehensive and reflects the areas of expertise of the committee and workshop participants. It does not cover all the technical areas within the NNR-NE. ONR could produce a more valuable list of opportunities by regularly and systematically exploiting the same sources that the committee relied on, that is, external consultation with practicing naval engineers, the operating Navy, researchers, and other technical experts. Later chapters will present the committee's evaluations of how well ONR's NNR-NE initiative makes use of such information to manage its research agenda and plan its portfolio.

RESEARCH NEEDS

The paper commissioned by the committee on potential technology implications of the Navy's future (O'Rourke 2010) identified three drivers that will probably have significant influence on the Navy's requirements for advanced platform technology: the future operating environments the Navy may face, the types of operations and missions it may expect to be called on to perform, and the prospects for availability of resources. Research needs dictated by each of these drivers are identified in the following three subsections.

Navy's Future Operating Environment

The implications of the future operating environment relate to a number of assumptions about future adversaries and the kinds of threats they may pose. Research may be required to counter or defend against new weapons that adversaries may use. Another issue may arise from limited or uncertain access to overseas land bases, which could, in turn, result in needs for either sea bases or ships with longer range, greater capacities, and smaller crews. The operating environment in Arctic regions as sea ice diminishes poses challenges for naval ships and crews. Finally, the need for energy conservation or use of alternative energy could require the Navy to exploit new technologies such as hybrid drive, fuel cells, and biofuels.

Threats from new weapons systems deployed by potential adversaries have been of recent concern to U.S. defense planners. Among those under consideration are antiship ballistic missiles or cruise missiles that have not been previously evaluated. These and other weapons could require Navy ships to support more capable radar and other surveillance technologies as well as to operate further outside the range of new weapons. In addition, certain future weapons threats may encourage the Navy to develop new technologies to reduce ship signatures. Another type of threat could involve new tactics, an example of which could be cyberwarfare. This threat could influence research needs for shipboard systems to increase resiliency or redundancy of computer networks. Finally, the threat of terrorist attacks could lead to ship technology needs concerning sensors and defenses against small boats, swimmers, unmanned submarines, and so forth.

Planners also have recently noted problems with regard to continued access to and vulnerability of certain U.S. overseas land bases that have traditionally been used by the military to support foreign deployments. This will likely result in more emphasis on overseas support by naval ships and other platforms, which will increase the need for cost-effective solutions.

The diminishment of Arctic sea ice is leading to increased human activities in the Arctic and is opening up a new operating area for Navy and Coast Guard surface ships. Technology implications, particularly for surface ships, of increased Navy operations in the Arctic include ice-strengthened hulls and underwater appendages, ice-resistant topsides, cold-temperature equipment, and so forth.

These factors are a few of many potential challenges facing the Navy in its future operating environment that could affect how ONR manages and plans its NNR-NE initiative.

Future Naval Operations

The second driver will be the character of the operations necessary to carry out the missions that the Navy will be called on to perform. Such operations include the traditional missions of sea control and power projection. Ballistic missile defense, counterterrorism and irregular warfare, antipiracy, and humanitarian assistance and disaster response are among the operations likely to have increased importance. These operational requirements will generate research needs to develop systems with unique functions for electronic warfare, to support the deployment of special autonomous vehicles, to support the use of special operational forces, to transfer relief supplies to shore, to repair damaged infrastructure, or to provide emergency medical and humanitarian support on a large scale in remote regions.

Additional needs may be generated by other special operations such as increased support systems for special operations forces; Sea, Air, and Land Teams; and the launch and support of autonomous unmanned vehicles (submersibles, surface vessels, and aircraft). Antipiracy requirements may involve unique new vehicles and surveillance systems. The current Navy program to build a series of littoral combat ships (LCS) are a direct result of these and related operational needs for smaller, more versatile platforms to operate in inshore and coastal waters and support special warfare operations. Many of the unique features that are incorporated on the LCS are a result of earlier research work in hydrodynamics, hull design, propulsors, materials, and structures.

Partnerships with other nations that can involve support of new naval capabilities in those nations and education and training missions appear to be growing in importance. The development of more effective training systems could create special research needs, as could the development of vessels and training modules for applications in a variety of foreign environments.

Finally, the Navy is being called on to support disaster response and humanitarian assistance efforts at an increasing rate, and its capabilities are sometimes uniquely suited to this mission. The adaptability of warships to these changing missions and special environments could lead to research requirements as well.

Resource Prospects

The third driver with implications for ONR's research portfolio will be the Navy's resource prospects and the influence of resources on all programs to design and build ships for future fleets. Most observers expect no real growth in the Navy's budget, and given increased pressures on federal budgets in general, a decline in Navy funding levels in coming years is a possibility. The affordability of the Navy's long-range shipbuilding plan in particular has become an annual topic of debate. For many years, Navy leaders have been making difficult budget choices between funding current operations and funding investments in future force structure. The coming years will be just as difficult in this regard. Some aspects of the Navy's resource situation may have technology implications. In particular, technology developments may affect such trends as increases in unit production costs for major naval combatants as well as overall operations cost increases. The rising cost trends have led to recent proposals for extending the life of existing ships and utilizing existing designs for new vessels rather than developing a new design class.

The affordability of ships is of great concern. A paper commissioned for this study identifies, as possible changes to reduce cost, "pervasive commonality . . . completion of ship design before starting construction . . . earlier involvement of shipbuilders in the design process . . . [and] modular outfitting and construction, test and insertion of payloads" (Sullivan 2010, 4). A reduction in the cost of the shipbuilding process has been addressed repeatedly by the Naval Sea Systems Command and shipyards. However, the cost of the combat systems and electronics payload does not appear to have been addressed to the same degree. It was first recognized about 25 years ago that the cost of the combat systems was beginning to exceed the cost of the rest of the ship. An intensified program of research will be necessary to develop the body of knowledge addressing ways to decrease the cost of such combat system elements as radars, missiles, and launchers. This research agenda should be aimed at making advanced, technically sophisticated combat systems entities less expensive. Although the problem of the cost of combat system elements is within the broad scope of naval engineering, research on the topic probably is beyond the scope of the NNR-NE initiative as it is defined at present.

More generally, research could also address the following deficiencies in the Navy's capability to manage cost: (*a*) a lack of robust capabilities to assess cost in the early stage of system development and (*b*) a lack of tools to investigate methods for decreasing the cost of combat systems elements. While tools to estimate ship cost are also largely undeveloped, the need is widely recognized. There appears to be little recognition of the need for tools to analyze the costs of combat system elements and methods for reducing them.

Other consequences of tightening budget constraints are the trend toward reductions in numbers of high-complexity, high-cost warships in the fleet; introduction of lower-cost, smaller vessels; and efforts to reduce ship recapitalization cost through life extension, use of common hulls and systems, and modular techniques. The Navy may find it advantageous to emulate the approach used in technology development for commercial ships by seeking careful incremental ship engineering evolution rather than revolution. Other technology improvements to reduce overall costs are automated systems that reduce crew size, provision of growth margins to increase life expectancy, systems to evaluate ship service condition and extend service life, and the use of unmanned vehicles for appropriate missions.

Summary Observations

Consideration of the future operating environment, future naval operations, and the future resource situation all point to the need for a high degree of reliable, intelligently integrated capabilities in future ships. ONR work in ship design addresses issues of total ship engineering as it relates to treatment of the hull, propulsion plant, and other systems, but research focused on subsystems as integrated entities at the ship level, including the combat system, is lacking. Thus, there is a need for research aimed at producing integrated combat systems as well as a more holistic approach to total ship systems engineering. The term "intelligently integrated" in this context is intended to convey the need for a level of system integration under which modifications and modernization are not impeded by an intertwining of functions that prevents separation and replacement of systems as new ones responsive to emerging threats or needed capabilities evolve. A key technology facilitating this flexible albeit tightly integrated ship systems approach is that of open architectures.

The above discussion has highlighted the committee's analyses of research needs based on the Navy's warfighting prospects. The analyses could provide input to ONR's management and planning processes for its NNR-NE initiative. While these drivers of future science and technology initiatives are important to understand and to refer to in the planning process, they are always subject to change, and therefore ONR must support a process that continually updates these factors and presents them to management and researchers at all levels. Chapters 3 and 4 outline and recommend such processes. Annex 2-1 reviews these factors on the basis of current analyses. It shows a classification of specific technology implications that ONR could consider in designing and planning its science and technology program in naval engineering and is provided as an example of how ONR planning might be aided by analysis of these trends on a regular basis. A similar process for evaluating and communicating future Navy needs would provide ONR with a useful planning tool.

SCIENCE AND TECHNOLOGY OPPORTUNITIES

This section provides examples of recent advances or promising developments in several technical disciplines that may present opportunities for improvement in the performance of naval ships. The Navy sponsors basic and early applied research not only to fulfill performance requirements identified by the fleet but also to ensure that such opportunities, arising from fundamental scientific and technological advances, are recognized and exploited.

Innovation can come from either of two sources. Increasingly demanding needs or requirements can "pull" the development of technology to meet the need, and scientific and technological advances can "push" the development of innovative naval systems. A past analysis of the driving forces for progress in naval engineering cites these two and adds a third factor: "wisdom . . . the ability to exercise good judgment relative to the requirements and technology available" (Comstock 1992, 4).

A paper commissioned by the committee (Friedman 2010) examines the sources of innovation in naval technology and gives historical examples of how both forces have driven progress in naval ship capabilities.

The paper examines the history of certain notable developments over the past century or more from the torpedo, the first submarine, and steam power to the aircraft carrier, nuclear power, and electronic warfare. The history of naval innovation provides valuable lessons for today's planners. One lesson is that the sources of innovation are always difficult to identify: "Few or none [of] the innovators consciously analyzed the character of sea power and then set out to develop something earth-shaking. Some of them must instinctively have grasped the implications of what they were doing. In most cases it is difficult to identify an individual with what is, in retrospect, an obviously decisive development" (Friedman 2010, 2). In addition, "the issue in innovation is always whether requirements or the innovator (or technology) dominates" (Friedman 2010, 3).

ONR appears to have, at a high level, processes acknowledging the push–pull paradigm, through technology advisory boards and supporting processes. However, as Chapters 3 and 4 of this report will illustrate, these processes have not been translated into NNR-NE processes, and they need to be developed for NNR-NE. A continuing challenge will be to ensure that program managers, deeply immersed in the intricacies of technology, always keep sight of the requirements for future systems. The committee's recommendations for processes that develop NNR-NE capabilities to anticipate and respond to push and pull research requirements are presented in the next two chapters. ONR requires enterprisewide processes, such as those proposed in Chapters 3 and 4, to ensure that the Navy is able to capitalize on both needs- and opportunities-driven science and technology advances to anticipate and respond to future mission requirements.

> **Recommendation:** In planning the NNR-NE research portfolio, ONR should search for research directions and research topics by identifying both (*a*) emerging scientific and technological developments that hold promise for providing new capabilities or new technology options and (*b*) gaps in fundamental scientific and technical knowledge that are hindering fulfillment of needs identified by the operating Navy. The search by ONR for research direction and topics should be systematized, adequately funded, measured, and incentivized and should be included as part of the organization's and its managers' performance evaluation processes. ONR could produce a valuable list of research opportunities through regular and systematic external consultations with practicing

naval engineers, the operating Navy, researchers, and other technical experts, and by documenting and publishing the research topic proposals generated by these consultations.

Most of the opportunities identified below were identified by the authors of the committee's commissioned papers and by the researcher participants in the committee's workshops. Authors of three papers (Triantafyllou 2010; Sullivan 2010; Firebaugh 2010) were asked for critical assessments of research and technology challenges and potential game-changing opportunities in naval engineering, emphasizing a 15- to 50-year horizon. In addition, they were asked to address new paradigms for the capabilities, operation, design, construction, or maintenance of naval vessels that could be realized through scientific and technological advances in naval engineering and associated fields.

At the June 2010 workshop organized by the committee (see Appendix A), researchers supported by ONR were invited to discuss the prospects for contributions to naval engineering from research in their fields. Each of the researcher panelists (as well as other researchers who did not attend) responded to the following questions relating to research opportunities:

- What are the most significant areas of challenge in your field of research in the next 20 years? What are the hard problems in your field? What are the obstacles to progress in your field?
- What directions or focus areas would you recommend for research investment in your field in the next 20 years?
- What are the best opportunities for breakthroughs in understanding or for the emergence of game-changing technologies in naval engineering?

The committee identified opportunities presented by recent advances in four of the NNR-NE technical areas—structural systems, hydromechanics, platform power and energy, and system integration—and opportunities in interdisciplinary collaborative research.

Structural Systems

Reduced numbers of new ship acquisitions and designs, as well as flat budgets, over the next several decades will require that ONR's structures research program place greater emphasis on the use of design and simulation tools in areas such as structural design and optimization, damage-tolerant designs, advanced materials, and life-cycle structural condition monitoring. Advances in mathematical modeling, computational algorithms, the speed of computers, and the science and technology of data-intensive computing have prepared the way for improvements in modeling, simulation, and computing.

Physics-based simulation enables users to produce virtual prototypes, realistically simulating the behavior of complex systems on computers and quickly analyzing multiple design variations until an optimal design is achieved. Structural design and computational fluid dynamics are simulation applications that can be used to develop optimized hull forms and structures that are more damage-tolerant.

Mathematical modeling for these applications involves a multistep process whereby designers generate computer-aided design (CAD) files, which must then be translated into analysis-suitable geometries, meshed, and input into large-scale finite element or other numerical analysis codes. For complex engineering designs such as the hull structure of a ship, this is a laborious and time-consuming effort. The significant advance made with the development of isogeometric analysis (T. J. R. Hughes, statement submitted to the committee, May 16, 2010) can be viewed as a fundamental game changer with its potential to unify CAD and engineering analysis methodologies.

Nearly all CAD, computer-aided manufacturing, and computer-aided engineering systems are based on nonuniform rational B-spline (NURBS) mathematical functions that are used to generate curves and surfaces of free-form shape. The development of isogeometric analysis uses the same NURBS geometry directly in the finite element formulations. This represents a new approach in finite elements, since the basis functions used in the finite element formulations are NURBS instead of the traditional interpolation or shape functions. It has also been shown that the numerical accuracy and robustness of the spline-based approximations are superior to those of the traditional finite element approach. The successful application of NURBS-based finite elements is one of the significant achievements associated with isogeometric analysis.

For practical design applications, isogeometric analysis eliminates differences between the CAD and finite element model geometries since they are one and the same, which greatly simplifies the design and analysis process, improves the geometric and numerical accuracy of the results, and reduces the overall design–analysis cycle time. Since isogeometric analysis is applicable to computational mechanics in general, there is also the potential for integration between engineering disciplines such as fluid–structure interactions. ONR needs to place priority on research in isogeometric analysis so that applications will be available for Navy ships in such areas as structures, hydrodynamics, fluid–structure interaction, computational mechanics, and electromagnetic signatures.

Research in developing improved technologies and models for monitoring, inspecting, and assessing the condition of ships in service and estimating their remaining service lives should also be a priority. With fewer new ships, the potential for extending ships' service lives (e.g., up to 40 or 50 years), and the possibility of sea swap (i.e., extended duration deployments with crew rotation) for ships deployed in ballistic missile defense, ships will be at sea for much longer periods. As ships in service age, their structural integrity is affected by corrosion and fatigue, which occurs when the ship's hull is subjected to repeated loading and unloading in sea waves. Corrosion and fatigue can result in damage to the ship and reduced service life.

In-service structural health monitoring of ships is an important component of their life-cycle management. Structural health management involves the ability to identify, locate, and characterize damage on a real-time basis and to predict the structure's performance and remaining service life. Such information is needed for making timely decisions affecting operational guidance, inspection, maintenance, and safety of a ship. For example, model-based structural health monitoring capable of treating uncertainty is a promising research direction. Research and advances in such areas as engineering mechanics, computational mechanics, applied mathematics, sensor technology, and signals processing will be required.

Corrosion control is a major problem in the maintenance of any ship, especially as ships age. New coatings that are durable enough to last the life of the ship are needed. Research into the development of nontoxic, ceramic nanoengineered coatings with significant potential for reducing resistance of the hull from their super-hydrophobic property and an ability to reduce biofouling and corrosion shows promise (Triantafyllou 2010). The Navy, within or outside of ONR, needs to focus more on coatings technology research.

Hydromechanics and Hull Design; Propulsors

Significant scientific and technical challenges continue to confront the areas of hydrodynamics, hull design, and propulsors. The following list identifies key subject areas and highlights relevant issues for each.

- Full-scale experiments: In the context of fundamental or academic research, results gained from such experiments continue to provide valuable information about the basic physics of the processes of interest. However, the ability to deploy such information in a more applied research and development (R&D) context, whether through empirically based models or by using the information to validate and extend numerical models, remains limited. More activity in this area is necessary.
- Capsize prediction tools: Capsize prediction tools based on mode advanced computational methods, such as free-surface Reynolds-averaged Navier–Stokes tools, have demonstrated viability in canonical model studies. However, the computational cost of using such tools is high, so in a design environment, tools for capsize predictions continue to be based on relatively simplistic numerical models. Further advances, at both the research and the application level, in capsize prediction tools based on the methods of computational fluid dynamics should be sought by taking greater advantage of the large-scale high-performance computing (HPC) resources available to the ONR community.
- Full-scale, broad-banded, unsteady multiphase ship-generated hydrodynamics, including fluid–structure interactions over a range of conditions: This is a complex problem, and an understanding of and the ability to predict it require development and application of multiple advanced computational techniques and their validation with data from experimental or full-scale measurement. A critical challenge on

the computational front is the limited development of new numerical models across multiple flow and structural scales and the ability to integrate them to investigate the full-scale, broad-banded problem. It can be argued that many currently supported research activities in modeling of multiphase hydrodynamics remain focused on mature rather than new numerical algorithms.

- Tools to see inside multiphase turbulent flows: Fundamental research activity in this area is strong; however, it should be given more support in a more applied R&D context. Without support, such tools will not mature quickly.
- Tool development in stochastic methods, extreme event statistics, and nonlinear system analysis: Fundamental research activity in this area is strong; however, it should be given additional support in a more applied R&D context through identification of relevant canonical problems and application of such tools to them.
- Data fusion relating to merging numerical and experimental data: In the aerospace community, data fusion methods for merging numerical and experimental data are regularly practiced and are well advanced. The ocean–naval engineering community should develop a research path in this area that builds on methods already developed and lessons already learned by the aerospace community.
- Passive and active flow control techniques: Activity in this area would be strengthened by better alignment between basic research and applications that would benefit from flow control. Basic research alone provides insight into the physics of canonical flow control, but without subsequent assessment of flow control technologies, the fluid mechanical advantages (if any) that are gained are not clear.
- Tools to support novel hull and appendage designs: Technical and scientific progress in these areas is feasible, and successes would likely lead to improved naval capabilities. The following are research areas that workshop participants cited as worthy of increased attention:
  - Improved integration of propulsor and hull hydrodynamic interaction on ships,
  - Predictive tools for propulsor performance in extreme ship motions (such as those caused by weather),
  - Interactive educational tools in propulsor design,

- Understanding of unsteady forcing and geometry designed with unsteady flow control,
- Improved methods for predicting effects of turbulence on fluid motion, and
- Ability to produce computational fluid dynamics model results in near real time.

As in the case of capsize prediction tools, further advances, particularly in numerical tools, at both the research and the application level should be sought by taking greater advantage of the large-scale HPC resources available to the ONR community. In addition, the limited development of new models is a challenge, since a number of currently supported research projects remain focused on mature rather than new numerical technologies.

Platform Power and Energy

The use of power electronics–based integrated systems to manage power and energy needs and efficiency is a technology that could have great impact on the performance of future Navy ships. Advances in the technology are the key to deployment of future high-power radar and electrically powered weapon systems, especially on smaller ships. ONR has adequately supported research on defining power electronics–based systems and design of components including converters, generators, storage systems, and design tools. However, research is needed on the dynamics of future power systems in which required weapons loads exceed available generation and on the problem of integrating future power and energy systems into overall ship design.

The following assumptions concerning the possible characteristics and capabilities of future power and energy systems may be made to guide planning of research and development:

- Propulsion, weapons, and practically all other functions including aircraft launching will be electrical. Several large ship hydraulic systems may use electric actuation, which will require energy storage to be fully integrated into the actuation system (e.g., control surfaces, blast deflectors, hatches).

- The power required, including that for pulse and short-duration load, will far exceed available generation, and therefore an integrated and distributed system along with some form of storage will be essential.
- Space and weight constraints prevent providing each weapon with its own power supply or storage.
- Fuel cells could have a significant role (although supplying the fuel remains a problem).
- Power electronics allow use of medium-voltage direct current, to eliminate transformers and circuit breakers.

The development of power and energy systems for future ships with these characteristics cannot proceed in isolation but must be conducted as an element of a total ship system design process. Examples of power and energy system design questions that can be answered only within the context of total ship system design include the following:

- Load requirements as dictated by the ship's speed, range, and duty cycle;
- Power management system requirements to accommodate different kinds of loads under normal operation and contingencies;
- The impact of pulse loading on the main and auxiliary gas turbine generators for determination of changes in mean time between failures, life expectancy, and ability of the turbine to follow rapid load changes (at present, there is no valid naval database for this type of pulse load operating scenario with large gas turbine generator sets);
- Forms of energy storage to be used (e.g., the ship's inertia may be a source for short-term loads);
- The impact of cable weight and dimensions on overall ship design and the value of reducing cable weight; and
- The impact of raising the main generation and distribution voltage level to reduce short circuit current levels, to lower cable weights, and to allow more cost-effective power electronics to be implemented at the upper end of the medium voltage level, such as 20 kV.

There is a need for basic and applied research on methods of integrating the development of future power and energy systems into overall ship design so that development of power systems can proceed with the assurance that critical constraints and trade-offs have been recognized and evaluated. Attention to the integration problem is essential if future ships are to accommodate the radar and weapon systems that the Navy wishes to use. It has been recognized that integration of distributed multiple energy storage subsystems on a surface ship (e.g., DDG-51 FLT III Class) can justify a lower overall power generation requirement and plant size for the array of gas turbine generators, further allowing an overall weight reduction in installed equipment. The use of energy storage can also allow a higher input power to the new radar transmitter systems, permitting better signal discrimination.

Developments in electric actuation for submarines can also be applied to surface ships for conversion of hydraulic systems such as hatch, door, and jet blast deflector operators to electric technology. All critical electric actuation requires a dedicated or common energy storage subsystem. New energy storage developments in battery and high-speed compact rotating machinery must be fully addressed, especially in regard to low-cost, higher-voltage systems.

As in the case of ship design tools, ONR planning for basic research in power and energy is likely to be productive only if there is clear overall Navy direction and planning for adopting power electronics–based and advanced rotating machinery–based power systems. There is a need in the U.S. defense industry for boosting development of 20-kV-level turboelectric machinery to counter the recent developments in Europe and Japan in compact turbomachinery. Identifying the research pathway that leads efficiently to the development of new power systems will require enterprisewide organization of basic and applied research, development, and testing. The organization must be a model of the process that the 2005 National Research Council Committee on Department of Defense Basic Research described as follows: "DOD should view basic research, applied research, and development as continuing activities occurring in parallel, with numerous supporting connections throughout the process" (NRC 2005, 2).

Basic and applied research areas that should be pursued to support power electronics–based integrated power systems are as follows:

- Advanced multidisciplinary design tools;
- Electrical system configurations and layout, distributed and zonal;

- High-frequency generators;
- High-speed, high-frequency compact drive motors;
- Variable speed drives;
- Fuel for fuel cells;
- Advanced controls, protections, and communications;
- Advanced power devices;
- Converter topologies permitting 8-kV to 20-kV direct current link voltages;
- Thermal management;
- Fault current management, including superconducting fault limiters;
- Storage: capacitors, batteries, flywheels, and ship motion;
- Hybrid energy storage such as combined rotating machinery–flywheel–battery systems;
- Power management, in normal conditions with high efficiency and also in emergency conditions;
- Solid prefabricated bus bars;
- Grounding;
- Arcing and advanced arc fault detectors;
- Insulation;
- Subsystem and system-level testing and demonstrations; and
- Information system for operation and maintenance.

System Integration and System Engineering

The NNR-NE portfolio presented to the committee appears not to include research on systems engineering methods themselves as applicable to the development of ships and other naval systems. A paper presented at the 2009 Conference on Systems Engineering Research included a discussion of "grand challenges" in systems engineering and includes the following observation applicable to complex naval systems (Kalawsky 2009):

> Systems engineering is rapidly becoming recognized as a key discipline in a number of sectors including Aerospace & Defence, Automotive, Construction, Energy, Transportation, Consumer Electronics, IT, Pharmaceutical & Healthcare and Telecommunications. This trend is driven by growing system complexity and the need for optimal integration of people, processes and technologies. Consequently, the sheer scale of future system complexity is likely to exceed our current understanding of systems engineering and the

> associated tools and techniques we employ. The number of overall system parameters to be controlled as part of the overall design process (as various system optimisations are undertaken) is likely to be overwhelming. Whilst systems engineers will be expected to manage system complexity the underpinning understanding of systems science, technology and tools must evolve to take account of the increasing systems complexity. Unless enabling research is undertaken there is a growing risk that available tools will be inadequate for the future.

The paper proposes a research agenda based on a series of grand challenges in systems engineering. Each grand challenge is a set of goals that are to be attained over the next one to two decades and that would constitute a major breakthrough in the field. The challenges proposed include development of an ultrascalable autonomous system architecture; verification, validation, and assurance of extremely complex systems; and total system representation in modeling and simulation (Kalawsky 2009).

Related problems that are central concerns of naval engineering and may be amenable to resolution through basic and early applied research but that are excluded from the six-field definition of NNR-NE's scope include the following:

- Estimation of acquisition, life-cycle, and producibility costs. Systems engineering and other research may be applicable to improving Navy cost-estimating capabilities.
- Tools for investigating holistic effects of ship service life on costs. The tools could help provide answers to questions such as the following: Does increased service life decrease overall cost? Would shorter service lives, with no modernization over the life cycle, be more cost-effective? Would the latter strategy result in a more robust industrial base or allow acquisition costs to be partially offset by sale of retired ships?
- Shipbuilding technology. While shipbuilding itself appears not to be included in any of the NNR-NE technical areas, it is mentioned prominently in the 2001 ONR memorandum defining NNR-NE. Shipbuilding, of course, is performed by industry, and mechanisms such as the National Shipbuilding Research Program exist to encourage the industry to initiate needed research in shipyard processes and efficiency.

Close relations between ONR and the shipbuilding industry would be likely to lead to identification of opportunities for NNR-NE research that complemented these industry efforts.

- “Smart” systems. It is apparent that automated and smart systems capabilities will be of growing importance with the emergence of all-electric ships, integrated electric propulsion, and the desire for operations that are both robust and robustly reconfigurable. The increased use of unmanned vehicles, some with autonomous capabilities, and the increased availability of smart sensors make total ship adaptive automation control of heterogeneous systems an alluring goal. An area that would likely benefit from the research in this area is shipboard damage control. Historically, this capability has been dependent on significant personnel resources. Smart automated and adaptive systems could provide the ability to configure shipboard systems rapidly to survive anticipated hits, to detect and evaluate damage and fire spread and provide guidance to crews, and to control deflooding systems.

Multidisciplinary Opportunities

Because large naval ships are among the most complex free-standing structures ever created and the most complex mobile structures, integration always has been a central problem of naval engineering (Triantafyllou 2010, 16). The preceding section noted the importance of research into system integration that seeks to discover general methods for optimizing ship design, given the constraints imposed by materials, structures, power systems, and hull and propulsor performance. This section describes research into a second kind of integration: research that integrates advances from multiple discrete scientific disciplines to open new technological opportunities.

Paper authors and workshop participants repeatedly emphasized the potential value of multidisciplinary research as a source of innovation in naval engineering and predicted that the best opportunities for breakthroughs will be through interdisciplinary initiatives and the leveraging of advances in other fields. They made the following observations (see Appendix A for reference to the presentations of K. Mahesh, T. Fu, S. Morris, and D. E. Hess):

- Exploiting advances in materials science and in chemistry will be key to progress on the hull design problems with which hydrodynamics is concerned.
- Biomechanics-inspired design also may lead to progress on hull design.
- Progress in fluid mechanics will be driven by collaborations among experimental, theoretical, and numerical investigations. Investments in basic numerical and experimental research using the combined strengths of these methods would advance knowledge of unsteady flow physics and the ability to design geometries that operate in unsteady flows.
- Research on hydrodynamic signatures and wakes is inherently interdisciplinary, involving hydrodynamics, vehicle dynamics and control, physical oceanography, and the physics of electromagnetic scattering.
- Current work in nonlinear systems, nonlinear control, deep machine learning, and remote sensing all could provide opportunities for major naval engineering breakthroughs.
- The advances in ship hydrodynamics are tied to mechanical and aerospace engineering, computer science, high-performance computing, and measurement system technology. Multidisciplinary collaboration has accelerated research accomplishments.

Workshop participants observed that naval engineering problems are generally not well known to researchers not directly engaged in the field, and therefore multidisciplinary collaboration must be fostered by promoting opportunities for technical interactions among university and naval researchers.

The committee commissioned a survey of emerging technologies from a multidisciplinary perspective and asked the author to speculate on potential game-changing opportunities (Triantafyllou 2010). The author argues that the discipline of naval engineering is being revitalized by capitalizing on scientific advances and new technologies from other fields and that leading-edge research is increasingly multidisciplinary. This trend is reflected in the increasingly diverse disciplinary backgrounds of new faculty in university departments of mechanical, naval, ocean, and marine engineering (Triantafyllou 2010, 1–2). The paper identifies eight emerging technologies with the potential to reshape naval engineering (Triantafyllou 2010, 1–2):

- Efficient power trains, including hybrid systems; efficient engines using alternative fuels; and fuel cells that use conventional fuels more efficiently;
- Advances in surface chemistry allowing development of novel coatings that can be used to protect ship hulls and cargo holds, to reduce deposits in pipelines, and to reduce fluid drag;
- New methods that are emerging from work on the all-electric ship concept to design and operate ships with increased automation, reduced manning, and increased reliability;
- New sensor arrays, which will allow sensing of self-generated flow and enable active flow manipulation and hence increased capabilities for maneuvering and efficient propulsion;
- Robotic developments that promise routine unmanned inspection and remote underwater intervention;
- Smart autonomous underwater vehicles that increase the operational capability of ships and submarines substantially;
- New high-strength steels that improve hull protection against impact and fatigue, including operation in very cold climates; and
- Global ocean modeling and prediction that will aid routing and operation of vessels in rough seas.

These technological possibilities arise from advances in a diverse array of fields, including materials science (high-strength steels, nanomaterials), chemistry (low-carbon fuels, fuel cells), electrical engineering (power electronics), information sciences (stochastic modeling), robotics, and computer sciences (high-speed computing for, e.g., real-time simulation of ocean wave fields for automated ship handling).

Summary Observations

The sections above identify particular areas of research that hold promise for advancing naval engineering and naval ship capabilities. Across these topical areas, the following two unifying themes emerge.

Conclusion: Basic research is needed on the problem of integrating ship systems, and research on components will stay on a productive course only if it is tightly linked to long-term programs of research and development of total ship systems. This need is especially apparent in the areas of power and energy systems and ship design tools.

Conclusion: It is likely that the future of naval engineering lies in incorporating advances from younger and rapidly advancing disciplines. If it is to maintain its relevance, the NNR-NE research portfolio must reflect this trend.

Recommendation: Because of the importance and complexity of emerging problems in naval engineering science and technology, along with demands for integrative and interdisciplinary research across all technological disciplines (NRC 1999), ONR should consider, as part of its continuous process improvement and assessment practices, adopting integrative and interdisciplinary metrics of performance in and across each of the NNR-NE functional areas.

The paper cited in the preceding subsection notes that ONR already is sponsoring initiatives that promote multidisciplinary collaboration, including the electric ship initiative (Triantafyllou 2010, 7).

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Abbreviation

NRC	National Research Council

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Annex 2-1

Technology Implications for the Future Navy

The table below lists technology needs arising from

1. The Navy's future operating environment,
2. Future naval operations, and
3. Future resource prospects.

In addition, it identifies implications of these needs for research priorities in ONR's NNR-NE. The table was prepared by the committee and is based on a paper commissioned by the committee (O'Rourke 2010).

1. The Navy's Future Operating Environment

Threat	Technology Need	ONR NNR-NE Implication
1. Adversaries with antiaccess weapons – China – Iran	• More capable shipboard radars • Improved networking technologies—linking ships with off-board sensors and networks • High-power directed energy weapons, particularly lasers • Improved terminal-phase (endoatmospheric) ballistic missile defense interceptor to augment the SM-3 exoatmospheric interceptor • Soft-kill options for countering antiship ballistic missiles • Mine countermeasures • Operating outside range of antiaccess weapons	• Next generation heating, ventilating, and air-conditioning; energy; and propulsion systems • Distributed, sensor-intensive hull, mechanical, and electrical networks (versus platform-intensive) • Integrated weapon systems; hybrid energy, hybrid network systems • Network, communication, electrical networks to support multiple attacks on kill chain • Antiship cruise missile as a potential game-changer

1. The Navy's Future Operating Environment *(continued)*

Threat	Technology Need	ONR NNR-NE Implication
		• Materials research—wake homers, damage control, absorbing warhead detonation • Hydroacoustics—wake homers • Distributed sensor networks • System integration—on board and off board; hybrid architectures • Damage control and fire suppression
2. Adversaries with cyberwarfare and antisatellite capabilities	• Protection and offensive capabilities for network, computing, communications, platform, and sensor protection	• Computer, network, data center, database, operating system applications – Redundancy – Availability – Maintainability – Resilience – Shareability – Security – Supportability – Sustainability • Distributed electrical, computer, network architectures • Virtualization—transfer services, capabilities, and security from hardware to software • Cloud architectures—software as platform, hybrid architectures
3. Adversaries with nuclear weapons	• Protection and offensive capability versus nuclear-armed states • Protection and offensive capability versus nonstate actors	• Hull, mechanical, and electrical structures hardened to overpressure, electromagnetic pulse, radioactive fallout • Materials protection, reaction, offensive capability

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1. The Navy's Future Operating Environment *(continued)*

Threat	Technology Need	ONR NNR-NE Implication
4. Terrorist and irregular warfare threats to forward-deployed naval ships	• Proliferation of antiship cruise missiles • Sensors, barriers, unmanned vehicles, lethal and nonlethal weapons for countering small boats, minisubmarines, and swimmers • Sensors and weapons for cost-effectively countering rockets and mortars • Topside equipment that can withstand rocket and mortar attacks	• Procurement strategies and measures of effectiveness (DDG 51 versus DDG 1000) • Hardened, absorbent, reactive, offensive materials • Materials and hull structures with embedded sensors, forensic analysis, autonomous damage control • Human system integration with hull forms, materials, sensors, structures
5. Limited or uncertain access to, and vulnerability of, overseas land bases	• Maritime Prepositioning Force of the Future [MPF(F)] • At-sea arrival and assembly of Marine forces • Launching Marine operations ashore directly from MPF(F) ships • Eliminate need to establish an intermediate land base	• Energy systems and solutions • On-board and off-board hull, mechanical, and electrical systems, sensor integration • Human–machine interface, integration • Nuclear propulsion • Self-healing–self-repairing, resilient systems, materials, structures, automation and mechanical systems
6. Diminishment of Arctic sea ice	• Increased human activity in Arctic • Arctic and cold weather operations, support, logistics, training, education, rescue • Comprehensive air, land, sea, maritime, space, submarine, and cyber monitoring • Maritime Domain Awareness	• Energy systems and solutions • Adverse weather monitoring, anticipation, routing, rescue, deployment, operational systems • Data analysis, cleansing, integration • Cyber and structure, hull, materials integration • New and strengthened materials, hulls, structures, propulsion systems, topside, integration systems • Hardened, ice- and temperature-resistant human–machine interfaces and systems (e.g., for managing fatigue, heat and cold, vigilance, etc.)

1. The Navy's Future Operating Environment *(continued)*

Threat	Technology Need	ONR NNR-NE Implication
7. Policy-maker focus on energy use and alternative energy	• Fuel expenditure reductions • Fuel-related logistics tail management • Department of Defense (DOD) petroleum dependence, vulnerability to disruptions in oil imports • DOD greenhouse gas emissions (mitigate DOD contribution, set example), without reducing military effectiveness • Energy-efficient shipboard equipment • Stern flaps, hull coatings, environmentally friendly coatings	• Energy-efficiency metrics, incentives, measuring systems • Hydrodynamic performance improvements • Fuel systems—alternative and bio, nuclear, organic, hybrid, electric, multiple phase and multiple drive • Propulsion systems: hybrid drive and electric drive, gas turbines, bio and alternative fuels, cells; kite- and sail-assisted propulsion • Energy systems—bio, alternative, electrical, solar, wind, grid and nongrid, hybrid architectures

2. Future Naval Operations

Threat	Technology Need	ONR NNR-NE Implication
8. Ballistic missile defense (BMD) operations	• Protection and offensive capability versus proliferation of theater-range ballistic missiles • Emergence of China's antiship ballistic missile • Administration choice to deploy Aegis ships for European BMD operations • Expanding BMD operations in coming years • 10 of 22 Aegis cruisers, and all Aegis destroyers, to be equipped for BMD operations • Integrating Aegis BMD with other elements of planned European BMD architecture • Adapting Aegis BMD into Aegis Ashore configuration • Developing MS-3 Block II-B missile to be used at Aegis shore sites	• BMD hull, mechanical, and electrical integration • BMD fuel, energy, electrical system, computing, communications, network bandwidth resource management • BMD safety, protection • Human factors research—vigilance; sleep deprivation; heating, ventilating, and air-conditioning impacts; electromagnetic emissions • Human factors crew swap out, multiple crew, reduced manning • Crew systems integration

(continued on next page)

2. Future Naval Operations *(continued)*

Threat	Technology Need	ONR NNR-NE Implication
	• Developing shipboard technologies for facilitating use of multiple crewing or sea swap on BMD-capable Aegis ships	
9. Counterterrorism and irregular warfare operations	• Protection and offensive capabilities versus counterinsurgency, stability, and counterterrorism operations • Support Navy Irregular Warfare Office, Naval Expeditionary Combat Command, riverine squadrons, Navy Foreign Area Officer program, naval civil reserve battalion	• Improved ship-based intelligence, surveillance, and reconnaissance (ISR) capabilities, including autonomous underwater vehicles capable of conducting persistent ISR operations • Expeditionary electronic warfare, signals intelligence, counterimprovised explosive device, explosive ordnance disposal, and riverine capabilities • Fast to target, low-collateral-damage strike weapons • Capabilities to covertly insert and recover Navy special operations forces; follow on to Advanced Swimmer Delivery System
10. Antipiracy operations	• Protection and offensive capability versus states • Protection and offensive capability versus nonstate actors	• Cost-effective antipiracy solutions • Improved ISR capabilities • Autonomous underwater vehicles for persistent ISR • Discriminating threats from nonthreats (pirates versus nonpirates) • Nonlethal weapons platforms, integration
11. Partner capacity-building operations	• Navy forces engage navies and coast guards of other countries to improve their capacities for conducting maritime security operations	• Improved education and training facilities, ship-based or portable modules • Language, organizational culture, multicultural training

2. Future Naval Operations *(continued)*

Threat	**Technology Need**	**ONR NNR-NE Implication**
12. Humanitarian assistance and disaster response operations	• Humanitarian operations • Strengthen U.S. relationships with assisted countries • Improve foreign public opinion of United States • Various ship types—hospital ships, amphibious ships, surface combatants, aircraft carriers, aircraft, especially helicopters • Technologies permitting field personnel to reach back to distantly located medical or other specialists for advice and information • Technologies to rapidly reestablish basic communications and civil governance	• Technologies permitting rapid detailed surveys and assessments of damaged areas and rapid dissemination of that information to the field (including airborne sensors) • Technologies for improved ship-to-shore transfer of relief supplies and equipment, particularly when airports and seaports are damaged and inoperable • Rapidly repairing damaged seaports and airports • Portable power generation, water purification, sanitary and medical care modules that can be installed aboard ship
13. Cyberoperations		

3. Future Resource Prospects

Threat	**Technology Need**	**ONR NNR-NE Implication**
14. Increases in ship and aircraft procurement costs	• Reductions in significant cost growth [littoral combat ship (LCS), F-35 Joint Strike Fighter] • Greater use of common hulls, systems, and components • Increasing modularity use in ship design and construction • Incorporating increasing design-for-producibility, improved production engineering	• Cost-effective materials • Materials, structures, systems, and integration that reduce cost, weight, size (electric drive equipment) • Technologies for reduced crews • Human–machine interfaces, human factors research for reduced manning • Improved construction processes and methods (National Shipbuilding Research Program)

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3. Future Resource Prospects *(continued)*

Threat	Technology Need	ONR NNR-NE Implication
15. Reduced ship and aircraft procurement rates	• Procure significant quantities of relatively inexpensive ships [LCS, Joint High Speed Vessel (JHSV)] • FY2011–2015 shipbuilding plan has 50 ships (25 of which are LCS and JHSV)—an average of 10 per year, compared to single-digit ships per year 1993–2009 • Beyond 2015, LCS and JHSV expire—SSBN(X) next generation submarine and few other ships • Increase percent of time spent on deployment • Increase use of unmanned vehicles	• Improved, more rugged, and more durable materials • Ships with greater growth margins • Ships with open architecture combat; hull, mechanical, and electrical systems; and physical open architecture features to facilitate modernization • Materials and techniques for corrosion control • Technologies and models for monitoring, inspecting, assessing condition of in-service ships and estimating their remaining service lives • Redundant, more reliable, self-repairing, and self-diagnosing systems • Multiple crew and sea swap technologies • Human factors, human–systems integration research for reduced crews, reduced crew operations, tasks, performance
16. Operations and support cost crowd out funding for procurement	• Improved estimates for total cost of ownership in design and evaluation of ships • CVN-78 USS Gerald R. Ford class aircraft carriers have life-cycle operations and support costs several billion dollars less than that of the Nimitz (CVN-68) class carriers • Increased use of unmanned vehicles as substitutes for manned	• Automation, integration, and systems design for reduced manning crews • Human factors research, human–systems integration research for reduced crew operations, tasks, performance • Improved performance monitoring of hull, mechanical, and electrical systems; topsides; structures; propulsion systems; electric grid, system and subsystems • Energy use and alternative energy solutions • Corrosion control and materials research

3. Future Resource Prospects *(continued)*

Threat	Technology Need	ONR NNR-NE Implication
		• Monitoring, inspecting, and assessing in-service ships • Open-architecture combat and other systems and physical open architecture features to reduce life-cycle modernization costs
17. Limited number of new ship and aircraft designs	• Greater use of common hull designs	• Strategies and technologies to introduce new capabilities through modifications to existing ship designs • Ship design and simulation tools to assess and simulate integration, use, failure, and response to failure • Road maps for introducing technologies (integrated electric drive and composite structures) into DDG 51 that were previously planned to be introduced through new acquisition procurement

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3

National Naval Responsibility for Naval Engineering Mission and Process for Achieving Goals

A robust naval engineering science and technology (S&T) enterprise that supports the needs of the current and future Navy must perform its core functions effectively and efficiently, consistent with its mission and the expectations of a high-reliability research organization (Pelz 1956; Roberts 1990). The core functions include

- Establishing the research agenda and allocating resources,
- Identifying performers,
- Measuring outcomes and evaluating results,
- Maintaining connections among the wider naval engineering community, and
- Developing the requisite human capital to sustain the nation's naval engineering capability.

While effective performance of these functions is necessary, it is not sufficient for success in complex, dynamic research enterprises (NRC 1999; National Academies 2005). In addition, a high-performance organization such as the Office of Naval Research (ONR) must clearly articulate its mission and goals; measure and reward performance against those goals; incentivize and educate participants about desired organizational performance; and develop a robust continuous process improvement activity that assesses organizational performance; communicates best practices and lessons learned; provides for systematic dissemination of goals, activities, and achievements; and assesses organizational, group, and individual performance over time (Roberts 1990; Grabowski and Roberts 1999). These challenges are compounded for research organizations whose missions involve interdisciplinary research, such as naval engineering. In such research organizations, measures and metrics of performance need to address the degree of integration and interdisciplinary activities required for mission success (National Academies 2005; Porter et al. 2006). This chapter presents a description of National Naval Responsibility for Naval Engineering (NNR-NE) core functions along with an examination of the NNR-NE's interdisciplinary and integrative science and technology efforts. It also examines how well ONR performs its core functions and how effectively it achieves successful outcomes.

ONR and its NNR-NE initiative have multiple processes and procedures in place that the committee believes are meant to support both the core and the integrative functions. For example, ONR has developed a *Naval S&T Strategic Plan* (ONR 2009b) that outlines the S&T vision and key objectives in 13 naval focus areas. ONR also tracks and reports on a variety of metrics, including the number of refereed papers that grow out of the projects it funds, the number of students it supports, and the number of advanced degrees completed by individuals its funds support. However, the committee sensed that these individual processes and procedures were not integrated into a cohesive whole that would support the alignment of NNR-NE's research agenda, resources, activities, and incentive structure to its goals or to measurable objectives and outcomes.

The following sections describe each of the NNR-NE core functions and how ONR's processes support the NNR-NE mission. In addition, alternative methods to enhance organizational, individual, research, and educational performance are presented.

ESTABLISHING THE RESEARCH AGENDA AND ALLOCATING RESOURCES

As discussed in Chapter 1, naval engineering was designated a National Naval Responsibility in a 2001 ONR memorandum that specified the purpose of the designation and the activities that were to constitute the NNR-NE (ONR 2001). ONR was already engaged in all or nearly all of the specified activities before the memorandum was issued. Rather than initiating new programs, the memorandum served as a declaration of policy: assigning the NNR designation indicated that (*a*) the listed activities are deserving of special priority in planning and budgeting at ONR because the identified S&T fields are critical to the Navy and no one else will support them and (*b*) management of these activities must be coordinated with the declared policy objective in mind.

The 2001 ONR memorandum set out the broad outlines of the organization's research agenda, envisioning an NNR-NE set of disciplines focused on the "development of educated and experienced people, expansion of the knowledge base, and cultivation of a climate supportive of innovation." It also called on ONR to "formulate and maintain investments" in these science and technology areas: ship design tools, ship structural materials, hydromechanics, advanced hull designs, ship propulsion, ship automation, and systems integration (ONR 2001).

ONR has regrouped the NNR-NE S&T areas as follows:

- Ship design tools;
- Structural systems;
- Hydromechanics and hull design;
- Propulsors;
- Automation, control, and system integration; and
- Platform power and energy.

Another category of activities that ONR includes within the NNR-NE definition is the University Laboratory Initiative, which concentrates on developing the future workforce and sustaining the education infrastructure for naval engineering. In the current grouping, ONR has combined hydromechanics and hull design into a single area; renamed the ship propulsion area as propulsors; added the power and energy area; and grouped automation, control, and system integration into a single area. The committee's analysis used the categories listed above.

The overall scope of the NNR-NE research agenda is shaped to a large extent by the size of the budget devoted to NNR-NE research projects. In FY 2009, the Navy devoted $44.1 million to basic and applied research within the NNR-NE domain (Table 3-1), 3.4 percent of the Navy's total $1.3 billion budget for basic and applied research (DON 2010, v, vii). The memorandum that established NNR-NE did not establish a preferred level of funding or share of ONR budget for activities to be carried out under the initiative.

The specifics of the research agenda are reflected in the projects that have been grouped under the NNR-NE technical areas. In presentations

TABLE 3-1 ONR Outlays for NNR-NE Basic and Applied Research, by Technical Area, FY 2006–2009

	Outlays ($ millions)					Average Annual Outlay per Project ($ thousands)
	2006	2007	2008	2009	Total, 4 years	
Automation, control, and system integration	**2.2**	**2.8**	**2.0**	**3.2**	**10.2**	**232**
Basic	1.6	1.8	1.1	1.8	6.3	233
Applied	0.6	1.0	0.8	1.4	3.9	231
Ship design tools	**2.4**	**3.4**	**3.0**	**3.0**	**11.9**	**165**
Basic	2.4	3.4	3.0	3.0	11.9	165
Applied	0.0	0.0	0.0	0.0	0.0	
Hydromechanics and hull design	**7.2**	**7.1**	**7.7**	**8.7**	**30.7**	**101**
Basic	4.8	5.5	5.5	5.4	21.2	94
Applied	2.4	1.6	2.2	3.3	9.5	121
Platform power and energy	**20.2**	**13.7**	**20.6**	**18.7**	**73.3**	**852**
Basic	1.4	1.3	1.4	1.9	6.0	136
Applied	18.8	12.4	19.2	16.8	67.3	1,601
Propulsors	**2.0**	**2.1**	**2.0**	**2.4**	**8.5**	**105**
Basic	0.8	0.8	0.9	1.0	3.5	82
Applied	1.2	1.4	1.0	1.4	5.0	131
Structural systems	**6.5**	**6.9**	**4.7**	**8.1**	**26.2**	**133**
Basic	4.1	3.7	3.7	3.5	15.0	106
Applied	2.4	3.2	1.0	4.6	11.2	203
Total	**40.6**	**36.1**	**40.0**	**44.1**	**160.8**	**205**
Basic	15.1	16.6	15.7	16.6	64.0	115
Applied	25.5	19.6	24.3	27.5	96.8	421

SOURCE: Tabulations of ONR 331 basic and applied research projects provided to the committee by ONR.

to the committee, ONR delineated its research agenda within these categories for FY 2009 by using a combination of specific examples of funded projects and summary tables showing the number of projects and the level of funding in each of the technical areas. Data on funding trends for projects in each area are provided in Table 3-1.

How much money ONR devotes to each of the NNR-NE S&T categories each year is a crucial factor in setting the research agenda. The 2001 memorandum establishing the initiative called on ONR Code 33 to "formulate and maintain investments in [all] seven key S&T areas in naval engineering." The memorandum was silent on how any funds should be apportioned among the areas, however.

ONR's 2009 project list within NNR-NE categories shows an investment profile with a large number of projects in hydromechanics and hull design ($8.7 million in FY 2009, or 19.7 percent of NNR-NE basic and applied research) and structures ($8.1 million, or 18.4 percent) and few in propulsors ($2.4 million, or 5.4 percent); ship design tools ($3.0 million, or 6.8 percent); and automation, control, and system integration ($3.2 million, or 7.3 percent).

Much of the $73 million in 2006–2009 platform power and energy funding was the result of a short-term initiative. The Navy's 2011 research and development (R&D) budget estimate reports a decline in all Navy applied research [Budget Area (BA) 2] spending for power and energy in 2010. Applied research funding for the budget category "surface ship and submarine hull mechanical and electrical (HM&E)" declined from $79 million in FY 2009 to $46 million in FY 2010 (DON 2010, 135). The budget estimate document states that "the funding decrease from FY 2009 to FY 2010 is due to the completion of the energy and power technology initiative that accelerated research in the following Energy and Power efforts: Distribution/Control and Alternative Energy efforts, Energy Storage and Power Generation efforts and the Medium Voltage Direct Current (MVDC) architecture efforts in support of the Next Generation Integrated Power System (NGIPS) Roadmap efforts," as well as the transition of some projects from applied research to the advanced technology development (BA 3) stage (DON 2010, 136). The Energy and Power Technology Initiative was a 5-year program begun in 2002 throughout the Department of Defense (DOD) to coordinate R&D on energy-efficiency technology improvements (Taylor et al. 2010).

ONR sees the development of a balanced portfolio as important: "Assessing the state of the health of Naval Engineering disciplines unique to the Navy is critical to ensure a *balanced* portfolio" (J. Pazik, briefing, Sept. 2009). That said, the annual share of NNR-NE designated projects and funding that go toward each of the technical areas depends on a variety of factors. The question becomes how ONR decides on the amount of money to allocate to each of those categories. Determinants include the success of ONR program officers in negotiating for projects in the NNR-NE technical areas for which they are responsible. It is not clear that program officers and ONR managers have used NNR-NE designation consistently as a determining factor in allocating funds to projects or in measuring the relative strength of the proposals submitted by offerors in response to ONR's broad agency announcements (BAAs).

The difficulty of planning and evaluating a basic research program should not be minimized. Outcomes often develop over years, and many important breakthroughs are unplanned. In developing its research portfolio, ONR appears to attempt to maximize outcomes by reliance on highly qualified managers with authority for program decisions, the tracking of short-term output indicators, feedback on the results of earlier efforts, advice from the technical community, and direction from Congress and the Navy. However, ONR does not appear to apply these informal processes explicitly to the NNR-NE as a coordinated program with specified objectives. (For example, program officers apparently do not consider whether an activity falls within the definition of the NNR-NE in making program decisions.) Furthermore, these informal processes do not match the requirements for monitoring and evaluation contained in the 2001 memorandum establishing the NNR-NE, which include monitoring of ONR's traditional output metrics for the NNR-NE as a unified initiative, strategic planning of the NNR-NE, monitoring of the health of the S&T enterprise supporting naval engineering, and annual reporting and periodic external review of the NNR-NE.

As a coordinating office that lacks direct authority over the funding and award decisions outside of Code 33, however, whether a project has NNR-NE designation generally does not determine in advance what share of the projects or funding will go toward each category. Moreover, as discussed in a later section, NNR-NE program officers strive to identify projects within their portfolios that most merit funding, even though individual NNR-NE program officers may include S&T areas that fall outside the NNR-NE purview. However, the committee could not determine whether anyone assumed responsibility for integrating research across NNR-NE functional areas or across naval weapons platforms.

Achieving balance in a research portfolio is a desirable goal and has been achieved in a number of research settings by using techniques such as the balanced scorecard method, which balances four perspectives to integrate quantitative and qualitative performance measures (Kaplan and Norton 1992). Studies evaluating the validity and strength of balanced scorecard methods have shown strong links between client or sponsor satisfaction and organizational performance, as well as between client satisfaction and economic variables such as client or sponsor retention, revenue, and revenue growth (Ittner and Larcker 1998a; Frigo and Krumwiede 2000).

Conclusion: The committee could not identify a process by which NNR-NE mission area needs and research strategies were prioritized. In addition, the committee could not identify any systematic process by which ONR research funds were allocated by NNR-NE mission area needs or prioritized research strategies. Instead, it appears that NNR-NE program officers fund research projects and principal investigators as opportunities arise, without an enterprisewide evaluation process that prioritizes and evaluates research project merit in a consistent manner across the NNR.

Conclusion: The committee did not find evidence that NNR-NE is measuring or achieving balance in its research portfolio, despite its stated balance goal. The committee found no metrics to measure or establish balance in a research portfolio, leading to questions about how such a portfolio could be balanced or could demonstrate balance.

Recommendation: ONR should establish an enterprisewide strategic planning and assessment process to develop a strategic plan for NNR-NE, link the plan to guiding goals and objectives, communicate those goals and objectives clearly throughout the naval research community, and evaluate and incentivize NNR-NE performance against the strategic plan and objectives. The NNR-NE strategic planning and assessment process should encompass all facets of the NNR-NE mission.

The strategic planning and assessment process should include a process for NNR-NE research fund allocation that is aligned with mission area needs and priorities so that resource allocation decisions are guided by a transparent, enterprisewide evaluation process that prioritizes and evaluates research project merit in a consistent manner across the NNR.

Recommendation: ONR should identify, utilize, and periodically reassess metrics to measure NNR-NE portfolio balance, in line with ONR's stated goals and articulated mission needs. Once established, these metrics should be incorporated into an enterprisewide assessment and continuous process improvement program, as described in subsequent sections of this chapter.

IDENTIFYING PERFORMERS

ONR generally makes its research awards in response to BAAs.[1] A consolidated annual BAA pulls together instructions to potential research performers for submitting award requests for a large share of ONR's projects, including those related to the NNR-NE. Most such awards are solicited through that consolidated BAA. For example, ONR released ONR BAA 10-001, Long Range BAA for Navy and Marine Corps Science and Technology, on September 18, 2009, with the expectation that it would remain open for 1 year. Proposals can be submitted at any time during the year (ONR 2009a).

Naval engineering research performers in the private sector include universities and industrial firms.[2] Research within the University Laboratory Initiative is conducted by universities. For allocating projects among university and industry performers, ONR relies heavily on its program officers' assessments of research merit, relevance to Navy missions, the value of sustaining long-term relationships with productive principal investigators, and the need to develop new promising principal investigators. ONR reported to the committee that program officers are mindful of the need to balance the long-term value of continued investment in ongoing research with research breakthrough opportunities and shorter-term needs for research transitions in a constrained funding environment.

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[1] ONR occasionally uses requests for information and requests for proposals to solicit research offerings. For example, Solicitation No. N00014-10-0001 requests proposals for a contractor to operate the Navy Metalworking Center and conduct research on technical projects related to metalworking. ONR also makes use of other instruments for support contracts.

[2] Basic research (Budget Activity 6.1) and applied research (Budget Activity 6.2) awards are usually provided as grants to universities and as contracts to industry. Advanced technology development (in Budget Activity 6.3) is usually performed under contracts. See ONR 2009a, 3.

Federally funded R&D centers, such as Rand, the MITRE Corporation, and the Department of Energy's National Laboratories, are not eligible to receive awards under ONR's consolidated BAA, although they may team with eligible partners. DOD laboratories, including the Navy's own laboratories and warfare centers, are also precluded from bidding directly.

ONR publishes on its website a list of technology areas in which it is interested, together with the names of and contact information for program officers who handle those areas. The BAA urges offerors to contact the program officer whose technology portfolio best matches their fields of interest before they develop their proposals.

Program officers are responsible for evaluating the technical proposals that are submitted in their technical areas. As stipulated by the BAA, award decisions are "based on a competitive selection of proposals resulting from a scientific and cost review." Box 3-1 lists the evaluation criteria to be considered in evaluating the BAA for 2010.

The BAA indicates that Factors 1 through 3—the technical factors—are of equal weight and that those technical factors are significantly more important than Factor 5, cost realism.

BOX 3-1

Evaluation Criteria for ONR's 2010 BAA

1. Overall scientific and technical merits of the proposal;
2. Potential Naval relevance and contributions of the effort to the agency's specific mission;
3. The offerors' capabilities, related experience, facilities, techniques or unique combinations of these which are integral factors for achieving the proposal objectives;
4. The qualifications, capabilities and experience of the proposed principal investigator, team leader and key personnel who are critical in achieving the proposal objects; and
5. The realism of the proposed costs and availability of funds.

SOURCE: ONR 2009a, 21.

One of the key inputs to the NNR-NE R&D process is knowledge of Navy needs and mission areas. ONR program officers often work as intermediaries between Navy laboratories, the academic and industrial research community, and other stakeholders. Such an integrative role is critical to the success of the NNR-NE initiative. The committee noted that links to the operational Navy community from designated NNR-NE projects were not as well articulated, nor could the committee identify a systematic mechanism that communicated Navy operational needs to program officers managing these projects. The committee concludes that no formal process exists within ONR for regular review of Navy mission needs relevant to its S&T planning for new projects with NNR-NE designation or for determination of allocation plans for funding to performer organizations.

ONR's performer evaluation process, including that for its NNR-NE portfolio, differs from that of some other government research sponsors in not including an evaluation of its basic research proposals by external peer reviewers. External review of proposals can be a valuable tool for government agencies that fund basic research, whose impact on future capabilities systems may not become apparent for decades. Organizations that use external scientific peer review for most or all of the basic research they fund include the National Science Foundation (NSF), the National Institutes of Health (NIH), and the Office of Research and Evaluation of the National Institute of Justice (DHS 2009). Within DOD, the Air Force Office of Scientific Research employs a peer review process using review panels that typically include two reviewers from other DOD offices and one from outside of DOD (Sharp 2007).

In contrast, the Defense Advanced Research Projects Agency (DARPA) generally does not bring external experts into its evaluation process. Instead, it uses its cadre of program officers, who typically rotate into the organization from positions outside of government and serve in DARPA for only a few years, thus ensuring a fresh flow of expertise and perspective. The committee understands that in recent years, ONR's program officers have stayed for substantially longer periods.

Supporters of ONR's proposal evaluation process argue that the community of scientists with relevant expertise—particularly in the naval engineering fields—is small, making it hard to find outside technical experts to serve as external peer reviewers. They might also point out that this committee's assessment constitutes an external peer review of NNR-NE's overall program and thus serves as an implicit review of the award choices made by NNR-NE program officers.

However, the committee found that there are sound reasons to consider bringing external peer scientists in to help with the evaluation of proposals. Bringing outside experts into the proposal evaluation process can help an organization sustain competition and avoid parochialism. It can also help to build a cohort of outsiders familiar with and interested in the particular areas of research. In NNR-NE's case, bringing experts from other government organizations into the proposal review process might help to forge and strengthen partnerships that the ONR organization aspires to develop.

Observers have found that external assessments like the one conducted by this committee can be useful in helping government research organizations to improve the merit and relevance of the research they fund and to develop plans for the future (Lyons and Chait 2009). Because such reviews are aimed at the organizational level, however, they lack the immediate impact on funded projects of external scientific reviews of proposals. The Navy Warfare Centers use peer-review evaluation, with external reviewers encouraged, for proposal selection in certain programs. Box 3-2 describes examples of the use of peer review of project proposals by research organizations within DOD and at other federal agencies. Box 3-3 summarizes conclusions of a 2002 National Research Council (NRC) study of approaches to organizing cooperative research on naval engineering, conducted at the request of ONR, concerning the value of peer review in the research programs it examined as models.

ONR leadership has formed a similar opinion with regard to the merits of external review in the monitoring of projects that have already been selected for funding and is establishing a peer-review process. The process described to the committee involves assembling a panel of three to five external technical experts who review the project's progress in the second (and potentially third) year of execution. The objective of these panels is to assess the efficacy of the ongoing project and to make recommendations to the program officer for continuation or termination. Unfortunately, this process does not appear to achieve all of the benefits that can be accrued through early participation of peers in project selection.

BOX 3-2

Examples of Peer Review of Project Proposals at Federal Research Institutions

The practices of research funding agencies in DOD and elsewhere in the federal government suggest numerous alternative arrangements for conducting peer review of research project proposals and reviews at other stages of research program management.

A survey of peer-review practices at Army establishments involved in R&D and at other federal agencies, conducted at the request of the Army Science and Technology Executive by the Center for Technology and National Security Policy, shows diversity in present practices and recommends best practices. The majority of the establishments reviewed were laboratories, but grant-making agencies (analogous to ONR) were included. The report describes review procedures applying to all stages of the production of scientific research, from project selection and program formation through work in progress to finished products, with the focus on individual projects or on the body of work of an organization.

The survey identified two Army research grant-making agencies that conduct external reviews of project proposals. The Army Research Office sends proposals for new, single-investigator research to external technical expert reviewers to evaluate technical merit. Separately, the proposals are also sent to Army and DOD scientists and engineers for evaluation of military relevance (Lyons and Chait 2009, 17). The Army Medical Research and Materiel Command sponsors and conducts research. Research proposals, including those from the command's researchers, are reviewed by an independent organization, the American Institute of Biological Sciences (Lyons and Chait 2009, 10).

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BOX 3-2 *(continued)*

Examples of Peer Review of Project Proposals at Federal Research Institutions

The Air Force Office of Scientific Research, which manages basic research for the Air Force, appears to have less standardized procedures but submits proposals in response to its BAAs to peer review in some circumstances. The office's *Proposer's Guide* states that "peer review and/or the scientific review process is used to conduct proposal evaluation" (AFOSR 2007, 5).

Other grant-making agencies reviewed in the Army study do not have external review of proposals. They include the Amy Research Institute for the Behavioral and Social Sciences, which submits proposals to an internal review process (Lyons and Chait 2009, 10).

The Army study describes peer-review procedures at NIH and NSF for comparison with those of Army and other DOD laboratories (Lyons and Chait 2009, 17). Both NIH and NSF routinely submit grant applications to external experts for evaluation. NIH research proposal peer review is governed by federal law and regulations (42 CFR Part 52h, Scientific Peer Review of Research Grant Applications and Research and Development Contract Proposals). At NSF, all proposals are sent to three to 10 expert reviewers outside NSF. Proposers may suggest reviewers for their proposals. The external reviewer evaluations are advisory. The NSF program officer recommends whether to fund each proposal, and final decisions are made by senior management (NSF 2011b, III-1).

BOX 3-3

External Review Conclusions of the Committee on Options for Naval Engineering Cooperative Research

NRC's Committee on Options for Naval Engineering Cooperative Research evaluated alternative organizational arrangements for a cooperative research program in naval engineering. The study was done at the request of ONR.

The cooperative research model is appropriate for a research program that must serve a diverse community of users and sponsors. These interested parties are given defined roles in guiding the program, including responsibilities in program planning and in project selection. The model might be applicable to a part of ONR's research related to naval engineering, if not necessarily all such ONR research.

The NRC committee reviewed governance arrangements in successful cooperative research programs, including NSF's Engineering Research Centers Program, the National Ocean Partnership Program, and cooperative research programs of the oil and gas industry (TRB 2002, 31). The committee also was aware of the cooperative research programs of the Transportation Research Board. In addition, the committee received proposals for cooperative research organizational structures from professional societies, university groups, the Naval Sea Systems Command (NAVSEA), and the National Shipbuilding Research Program (TRB 2002, 31).

The committee reached general conclusions on essential organizational features on the basis of the experience of the established research programs and the advice of the interested groups. With regard to external participation in the selection of research

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BOX 3-3 *(continued)*

External Review Conclusions of the Committee on Options for Naval Engineering Cooperative Research

projects, the committee concluded that "in a true cooperative program, all the major stakeholders have both a shared interest and shared ownership in the research agenda. For any of the organizational models to be successful, it must provide a structure and mechanism to allow appropriately balanced representation and input to the research agenda from stakeholders" (TRB 2002, 7).

With regard to evaluation in general, the committee concluded that "to be successful, merit review of the research . . . should take place at three stages in the process: when the proposal is approved, annually during the course of the research work, and when the project is completed. A merit review panel should be carefully balanced to ensure that innovative high-risk ideas are not lost and that the results address the Navy's needs. . . . The small size of . . . [the naval engineering research] community will necessitate resourcefulness in assembling a qualified and conflict-free group of individuals with balanced biases as reviewers for research proposals, progress, and outcomes" (TRB 2002, 7).

At the January 2010 committee workshop, a Warfare Centers participant identified the function of the mission capability manager as a possible model for ONR to emulate. Naval Undersea Warfare Center (NUWC) Newport Division (ND) uses mission capability managers who understand specific end-to-end Navy missions (e.g., antisubmarine warfare–antisurface warfare) and who are responsible not for specific projects but for ensuring that the center delivers mission capabilities that are required (P. Corriveau, briefing to the committee, Jan. 13, 2010). The mission capability manager facilitates communication and optimizes knowledge-sharing within the center to enhance the relevance of research efforts through cross-departmental collaboration and leverage.

Conclusion: External peer review (i.e., review by technical experts from outside ONR) throughout the research project selection process offers the opportunity to strengthen research project selection and to obtain the advice and counsel of technical experts, Naval Sea Systems Command (NAVSEA) technical authorities, and industry practitioners who are the ultimate recipients of the developed technology, while maintaining the ONR program officer's independence in making decisions for his or her program.

Recommendation: ONR should establish a process for NNR-NE (and potentially other programs) in which the program officer assembles a small group of Navy laboratory technical experts [e.g., from Naval Surface Warfare Center (NSWC) Carderock (CD)] and NAVSEA technical authorities (who also serve as industry surrogates) to review, assess, and rank relevant proposals received in response to ONR BAAs. The program officer then would be responsible for considering these recommendations and selecting projects. The midproject external review that ONR already conducts would be carried out by this panel with the addition of external reviewers according to the requirements of the present midproject review procedure. The proposal review panel would not remove ultimate responsibility from the program officer. Instead, the panel would create a dialogue and open lines of communication among ONR and the key Navy constituencies.

Recommendation: As input to the identification of performers, to enhance systematic dissemination of Navy mission and needs, and to improve communications between ONR and operational Navy units, NNR-NE should use mission capability managers who are responsible for understanding specific end-to-end Navy missions.

Recommendation: To improve communication of operational requirements and the transitioning of technology to naval ships, ONR should implement the concept of a technology interpreter in the NNR-NE. The task of the technology interpreter would be to assist in the technology transition process. The recommended peer-review panels would implement the concept of a technology interpreter in the program officer and technical authority communities. Frequent communication between these communities would inform

> the program officer of technologies that the technical authorities need and want and inform the technical authorities of new technologies as they emerge and mature. In combination with the review panels, personnel dedicated to improving communications and execution could significantly improve NNR-NE integration with Navy missions, needs, and operational requirements.

Case studies where such informal dialogue between program officer, technical expert, technical authority, and industry have been most constructive and successful are documented in the committee's commissioned papers (Hackett 2010; Doerry 2010). Doerry (2010) discusses the concept of relationships managers, "individuals that assist the technology transition process," which has been identified by the Government Accountability Office as an industry best practice (GAO 2006). "Technology interpreter" may be a more descriptive term for this role.

MEASURING OUTCOMES AND EVALUATING RESULTS

In recent decades, the executive branch and Congress have emphasized the importance of setting goals and measuring progress toward them as a way for federal departments and agencies to improve their performance, develop relevant plans for the future, and build budgets. The Government Performance and Results Act of 1993, P.L. 103-62, requires federal agencies to prepare strategic plans, annual performance plans, and annual performance reports. The plans are meant to identify concrete, measurable goals and objectives and schedules for meeting them. The performance reports are meant to explain how well actual performance measures up to the plan and what the agency plans to do to narrow the gap between plans and performance.

Although such documents are not generally required at the subagency level, high-performing research units recognize the importance of commitments to assessment, measurement, and continuous process improvement (Roberts 1990; Roberts and Rousseau 1989). High-performing lower-level organizations thus often derive their plans and objectives from the strategic plans formulated at the department or agency level. Components of an enterprisewide, systematic assessment process include metrics for measuring and incentivizing performance; a continuous process improvement activity that considers the outcomes of the metric evaluation processes; a benchmarking operation to determine organizational progress over time; and a systematic communication method to promulgate lessons learned, best practices, and organizational heuristics (Bond 1999; Brown 1996). As an illustration, Box 3-4 describes current performance assessment and strategic planning initiatives at NSF.

> **Conclusion:** ONR collects information on a variety of metrics that could be helpful in evaluating progress toward objectives, incentivizing performance, and improving the organization over time. However, it was not clear to the committee that these metrics are linked to a set of measurable objectives for the S&T enterprise in NNR-NE. The committee also could not determine whether any NNR-NE guiding goals or objectives were tied to strategic plans at the department or agency level. The committee was unable to identify an NNR-NE strategic plan that establishes priorities and identifies measurable objectives, an annual performance plan, or annual performance reports.

R&D portfolios are a composite of short- and long-term programs, collectively designed to foster discovery and innovation in support of an organization's mission. Evaluations of R&D portfolios often measure the completeness, robustness, strength, and degree of innovation present in the portfolio (Reugg 2007). To measure performance, organizations often apply quantitative performance measures such as return on investment or earned or economic value added, along with nonfinancial measures such as stakeholder or sponsor satisfaction and measures of the quality of the research and innovation supported (Ittner and Larcker 1998b; Kaplan and Norton 1996a; Kaplan and Norton 1996b; Kaplan and Norton 1996c; U.S. Department of Energy 1995; U.S. Department of Energy 2001). Research portfolio outcome and process metrics are often integrated to develop a more holistic view of the portfolio's performance and promise (Yeniyurt 2003; Eccles 1991; Eccles and Pyburn 1992; Kaplan and Norton 1992; Kaplan and Norton 2004; Ittner and Larcker 1998b; Tan and Platts 2003; Tan et al. 2004). A commonly used approach is the balanced scorecard method, which balances four perspectives to integrate quantitative and qualitative performance measures (Kaplan and Norton 1992).

BOX 3-4

NSF's Performance Assessment Framework

A number of federal agencies that sponsor or conduct research have implemented enterprisewide information and reporting systems that provide performance metrics and information for assessment and continuous process. NSF, in its *FY 2012 Budget Request to Congress,* describes its current efforts to strengthen performance assessment (NSF 2011a, Performance Information-3):

NSF is reviewing its performance assessment framework, in keeping with the Administration's commitment to establishing an evaluation infrastructure that complements and integrates efforts to strengthen performance measurement and management. This overall effort has been a specific focus of the recent update of the NSF Strategic Plan, which places special emphasis on testing and refining new approaches to assessment and evaluation. The FY 2011 GPRA [Government Performance and Results Act, P.L. 103-62] Performance Plan . . . is the first such plan based upon the new Strategic Plan.

A number of related efforts are also underway. These include:

- Continued progress toward NSF's STEM [science, technology, engineering, and mathematics] Workforce Priority Goal.
- Sustained NSF support for the multi-agency data infrastructure for monitoring and analyzing investments in science and engineering research and education [STAR METRICS (Science and Technology for America's Reinvestment: Measuring the Effect of Research on Innovation, Competitiveness and Science), a multiagency initiative to develop a data infrastructure to support evaluation of federal investment in research and development]. . . .

- The establishment of an NSF-wide capability for assessment and evaluation planning for an expanded NSF-wide assessment and evaluation capacity.
- Systematic efforts to improve evaluation and monitoring activities in STEM education and workforce programs.

NSF's 2011–2016 strategic plan identifies, as one of its three strategic goals, performance as a "model organization." This goal "sets high standards for attaining excellence in operational activities, promotes a culture of integrity and accountability, and encourages new approaches to assessment and evaluation of NSF's investment portfolio" (NSF 2011a, Overview-2). NSF states that the three goals, "Transform the Frontiers, Innovate for Society, and Perform as a Model Organization—lay out a path towards both longer-term outcomes and the more immediate impacts NSF's investments can generate" (NSF 2011a, Performance Information-3).

The importance of intellectual capital in an R&D portfolio suggests the need to incorporate measures of a portfolio's intangible assets, in addition to balancing outcome and process measures (Yeniyurt 2003; Kaplan and Norton 2004). Skandia Insurance Company, for instance, uses assessments of human, intellectual, structural, and brand assets; intellectual property; and customer capital to evaluate its intangible assets (Edvinsson 1997; Edvinsson and Malone 1997; Joia 2000). Intellectual capital is often thought to be a function of human capital, structural capital, customer capital, and innovation capital, with the relationships among these factors varying by institution, available resources, and setting (Yeniyurt 2003; Chen et al. 2004).

Other metrics have been proposed for intellectual capital criteria, including creativity and productivity, which vary according to individual attributes, task characteristics, and organizational contexts (Chang and

Birkett 2004). Comprehensive assessments of R&D portfolios therefore balance a number of criteria. First, they consider whether the portfolio's goals are aligned with the mission of the parent organization or sponsor. Second, they use quantitative and qualitative performance measures along with metrics to assess the intellectual capital, creativity, and productivity of the intellectual enterprise. Finally, they assess the balance, completeness, and expected longevity or sustainability of the portfolio, along with intangible factors such as management and investigator enthusiasm and commitment, and the importance of the expected impact of the portfolio on the organization and its wider setting (Bukowitz and Petrash 1997; Kaplan and Norton 2001; Kaplan and Norton 2004; Melnyk et al. 2004).

Measuring outcomes in complex interdisciplinary research on an annual basis can be challenging because of its inherent unpredictability, but measures do exist: measures of *quality,* in terms of research advancement; *relevance,* in terms of application development; and *leadership,* in terms of the ability to take advantage of opportunities when they arise, as evaluated by experts and users of research (NRC 1999, 9). In addition, human resource development has been identified as a key outcome of an effective research program. A remaining challenge is to determine what additional measures, if any, are needed to evaluate interdisciplinary research and teaching beyond those shown to be effective for disciplinary activities. Successful outcomes of an interdisciplinary research program differ in several ways from those of a disciplinary program. First, a successful interdisciplinary research program will have an impact on multiple fields or disciplines and produce results that feed back into and enhance disciplinary research. It will also create researchers and students with an expanded research vocabulary and abilities in more than one discipline and with an enhanced understanding of the interconnectedness inherent in complex problems (NRC 2004, 150). The following section presents the committee's assessment of NNR-NE performance with respect to aligning NNR-NE activities with Navy S&T strategic plans, ensuring consistency with NNR-NE objectives, and measuring and improving NNR-NE outcomes. The committee then presents its assessments of NNR-NE performance with respect to integrating NNR-NE activities and performing interdisciplinary research.

Aligning NNR-NE Activities with Naval S&T Strategic Plans

During the past decade, the Navy has developed strategic plans for its S&T efforts. The most recent of these is the 2009 *Naval S&T Strategic Plan: Defining the Strategic Direction for Tomorrow* (ONR 2009b), developed jointly by ONR and the Naval Research Laboratory and signed by the senior uniformed and civilian leaders of the Navy and Marine Corps forming the S&T Corporate Board. The strategic plan outlines the S&T vision and key objectives in 13 naval focus areas, which are listed in Box 3-5.

Within ONR, the two-digit offices identify the focus areas that they support. On its website, ONR's Code 33 (Sea Warfare and Weapons, which houses the NNR-NE) lists its focus areas as fleet and force sustainment, maritime domain awareness, power projection, and power and energy.

BOX 3-5

Naval S&T Focus Areas in 2009 *Naval S&T Strategic Plan*

1. Power and energy*
2. Operational environments
3. Maritime domain awareness
4. Asymmetric and irregular warfare
5. Information superiority and communication
6. Power projection
7. Assure access and hold at risk
8. Distributed operations
9. Naval warfighter performance
10. Survivability and self-defense*
11. Platform mobility*
12. Fleet and force sustainment
13. Total ownership cost*

*Naval S&T focus areas most closely related to the scope of NNR-NE (ONR 2009b, 8–25).

Surprisingly, the website does not list survivability and self-defense, platform mobility, or total ownership cost even though much of these three focus areas relate directly to the NNR-NE technical areas and other Code 33 core programs. This apparent disconnect is emblematic of the issues related to linking the NNR-NE activities with the *S&T Strategic Plan.* Such connectivity is key to obtaining support within the ONR organization that would be reflected in appropriate investment levels for an NNR focus area.

Table 3-2 highlights the objectives for each of those focus areas as outlined in the *S&T Strategic Plan.* Many of the objectives listed in Table 3-2 are related to NNR-NE's mission of developing educated and experienced people, expanding the knowledge base, and cultivating a climate supportive of innovation in the S&T categories that fall within its purview.

The objectives on this list, and more generally the objectives highlighted among all 13 focus areas of the 2009 ONR strategic plan, might be a useful starting point for NNR-NE in identifying the broad categories of work in which the Navy has higher-priority interest. In that sense, they may provide useful guidance to the NNR-NE program officer who is faced with choosing among the projects offered by universities and industry. As discussed below, however, it is not clear how one would use them to measure progress toward goals.

Ensuring Consistency with NNR-NE Objectives

NNR-NE has developed a list of objectives for the work done within each of its six S&T categories as well as for its University Research Initiative. However, it was not clear to the committee how those NNR-NE objectives are aligned with those of ONR's *Naval S&T Strategic Plan* (ONR 2009b). The committee was also unable to find evidence that NNR-NE set measurable objectives related to the S&T categories under its purview. In one example, objectives for the structural systems category include the following:

- Develop technologies for life-cycle performance analysis and monitoring of ship structural systems;
- Develop an understanding of behavior of novel ship structures, such as composite or aluminum subsystems, during and after fire to enable modeling and prediction;

TABLE 3-2 Objectives of the S&T Focus Areas Supported by ONR Code 33

Focus Area	Objectives
Fleet and force sustainment	Sea-based sustainment • Flexible and responsive warehousing • At-sea assembly and reconstitution of forces Flexible and responsive delivery systems • Point-of-delivery systems • Heavy-lift vehicle launch and recovery • Ship-to-shore logistics Integrated logistics • Common operating picture—logistics • Autonomous resupply systems • Source-to-objective asset visibility
Maritime domain awareness	Pervasive and persistent sensor networks • All domain coverage • Mission-focused autonomy with near real-time self-tasking • Secure, survivable, self-healing, adaptable, and affordable Identification of hard targets through diverse sensing • Identification of entities and events via electromagnetic signatures • Development of SIGINT capability to understand human activity • Characterization of acoustic signatures • Use of tagging, tracking, and location to declutter battlespace picture Sensor and data integration and threat assessment • Automated image, video, and SIGINT processing • Rapid, accurate, multisource data integration including national and tactile sensors, intelligence, and open-source data • Automated decision tools • Automated ISR sensor retaskings to refine battlespace knowledge Automated assessment of events and entities to determine intent
Power and energy	Energy security • Alternative and renewable energy sources • Future logistics tools • Resilient power networks and systems Efficient power and energy systems • Materials, devices, and architectures to increase efficiency and power density for platforms and reduce weight for personal power • Efficient power conversion, switching, distribution, control, and thermal management • Engines, motors, generators, and actuators • Electromechanical, thermal, and kinetic energy storage High energy and pulse power • Energy storage power system architectures • Energy pulsed power switching and control systems

(continued on next page)

TABLE 3-2 Objectives of the S&T Focus Areas Supported by ONR Code 33 *(continued)*

Focus Area	Objectives
Power projection	Future Navy fires • Increased fires volume and accuracy • GPS-denial compensation • Indirect fires to 250 miles from safe offshore locations • Long-range surface warfare capability Control collateral damage • Scalable effects weapons • Selectable and directional lethality Time-critical strike • Hardened target–moving target reach and destroy • Worldwide to meet warfighter requirements Small-unit combat power • Increased small-unit weapon lethality • Neutralize larger hostile forces • Application of Joint Fires • Advanced weapon sights, including multispectral Combat-insensitive munitions • Reduce system sensitivity to sympathetic detonation • Maintain payload range and lethality
Survivability and self-defense	Platform stealth • Reduce aircraft, above-water, and subsurface signatures • Multispectral LO technologies Force protection • Detect and determine threat intent to interrupt kill chain • Detect and deter small boat and unmanned threats • Antiswimmer technology • Nonlethal response Countermeasures and counterweapons • Threat weapon tracking and weapon–countermeasure–sensor selections • Automated decision making and battle management aids • Low-false-alarm-rate, 360-degree detection • Hard kill and soft kill against threat kinetic weapons • Extend standoff to beyond threat damage range • Directed energy weapons for speed of light engagement • Counter-LO capabilities Survivable platforms • Advanced platform construction materials • Damage-tolerant platform architectures • Automated damage-control focusing • Advanced materials for self-healing platforms

TABLE 3-2 Objectives of the S&T Focus Areas Supported by ONR Code 33 *(continued)*

Focus Area	Objectives
Platform mobility	Efficient, high-endurance, high-speed platforms • New and novel advanced platform design supporting new directions in naval warfare (size, agility, modularity, etc.) • Higher-performance platforms at reduced fuel consumption • Efficient, all-terrain, lighter, more agile ground vehicles including suspensions and drivetrains • Manned vessel launch and recovery • Operator guidance tools • Lightweight, higher-strength advanced composites and structural metals for optimized platform performance
	Vertical lift operations in challenging environments • High-performance vertical and short takeoff and landing • High sea states launch and recovery technology to enable manned or unmanned air operations
	Autonomous and unmanned vehicle mobility • New unmanned platform design technology • Advanced robotic systems for air, ground, and sea combat • Unmanned vessel launch and recovery
Total ownership cost	Platform affordability • Advanced modeling and simulation for design, test, and evaluation • Advanced naval materials • Open architecture for hardware and software • Low-cost, reliable sensors and electronics • Innovative manufacturing technologies
	Maintenance and life-cycle cost • Condition-based maintenance systems • Anticorrosion and antifouling technologies • Wear-resistant lifetime materials • Energy-efficient systems • Software reliability
	Manning optimization • Human–systems integration • System automation • Autonomous systems

NOTE: GPS = Global Positioning System; LO = low observable; ISR = intelligence, surveillance, and reconnaissance; SIGINT = signals intelligence.

- Provide protection system and armor that can defeat several threats and meet structural and stiffness requirements; and
- Facilitate use of alternative hull forms that have a longer life than steel or aluminum hulls and are lighter, more survivable, stealthier, cheaper, and easier to maintain (J. Pazik, briefing, Sept. 2009).

Such objectives clearly help guide the structural systems program officers and potential offerors concerning which research areas to pursue, although the intent of some of the objectives is unclear. In the case of the second objective, "develop an understanding of behavior of novel ship structures," for example, the committee could not ascertain how such an understanding could be reached or improved in a measurable way.

The objectives on the ONR 2009 strategic priorities list, and more generally the objectives highlighted among all 13 focus areas of the 2009 ONR strategic plan, should be a starting point for NNR-NE in identifying the broad categories of work in which the Navy is interested.

The research objectives for NNR-NE that ONR establishes in the recommended enterprisewide strategic planning and assessment process should relate to its three interrelated missions: developing educated and experienced people, expanding the knowledge base, and cultivating a climate supportive of innovation. For example, ONR might establish a goal for the number of undergraduates, graduates, and postdoctoral candidates to be offered fellowships each year. For graduate students and postdoctoral candidates, ONR might simply adopt the goal set by NNR-NE's founding memorandum of October 22. 2001: "Develop about half of the 'pipeline' of future naval researchers required to sustain the expertise in naval engineering"—"about 5 graduate fellowships and 5 post-doctoral candidates per year" (ONR 2001, 4).

Developing a measurable goal for the expansion of the knowledge base can be difficult, especially for basic research, where it can take decades for the knowledge developed to bear fruit. Some high-performing research organizations gauge their progress by using surrogate measures. For NNR-NE, traditional measures of knowledge base expansion might include the number of articles on work funded by NNR-NE that are published annually in peer-reviewed scientific journals, the number of citations of work funded by NNR-NE in such journals, or the number of scientific or engineering awards received by those whose work was funded by the organization (DHS 2009). However, more recently, research organizations have also adopted measures representative of the integrative, interdisciplinary research required to address current and future grand challenges (Porter et al. 2006; National Academies 2005).

For NNR-NE, integrative measures of research underscore the importance of total ship solutions in naval engineering, recognizing the constraints placed on hydrodynamics; structures; propulsors; power systems; and automation, control, and systems engineering by a restricted platform operating envelope and naval missions. Thus, integrative metrics encourage program officers and principal investigators to consider research priorities and directions holistically and across platforms, rather than pursuing research success in a single functional area (e.g., hydrodynamics) or on single platforms.

The committee identified several notable examples of excellent NNR-NE integrative research projects during its workshops and information-gathering activities (e.g., the advanced integrated mast, composites research) and in its commissioned papers (Hackett 2010; Hagan 2010), which provide an initial platform for integrative NNR-NE research. ONR actions to build incentives for multidisciplinary research initiatives into the management of the NNR-NE are recommended at the end of this chapter.

NNR-NE integrative metrics could include the number of interdisciplinary projects, the number of interdisciplinary publications, impact measures of research conducted within and outside of primary disciplines, citations and funding received outside of primary disciplines, and the numbers of publications and citations within a single discipline and across multiple disciplines. Such metrics encourage program officers and principal investigators to adopt interdisciplinary perspectives in the research projects, and they encourage program officers to look for opportunities for collaboration across naval engineering S&T and across ONR to address critical naval research priorities.

For applied research or advanced technology development projects, NNR-NE might develop objectives related to technology transition into Navy R&D projects at the BA 3 level and above. Because the development of a climate of innovation is also one of the organization's charter missions, it appears that NNR-NE should also develop objectives related to this area.

The committee noted that several of the integrative research projects so critical to future advances in NNR-NE were the outgrowth of an

NNR-NE program officer's or an industry representative's individual leadership or foresight, rather than the natural result of an enterprisewide research strategy, planning, and prioritization process or of organizational structures (e.g., technology interpreters) designed to produce cross-cutting, integrative advances across the NNR-NE.

Measuring and Improving NNR-NE Outcomes

This section suggests a template that ONR might use to integrate and delineate information and data that it already collects into a more coherent picture that could be used to measure progress toward desirable outcomes. The template is based on the three goals identified in the NNR-NE chartering memorandum: "(1) provide and sustain robust research expertise in the United States working on long-term problems of importance to the Department of the Navy [knowledge]; (2) ensure that an adequate pipeline of new researchers, engineers, and faculty continues [people]; and (3) ensure that ONR can continue to provide superior S&T in naval architecture and marine engineering [transition]" (see the committee's statement of task in Box 1-1). ONR currently collects information related to these areas, as follows:

- Knowledge
  - Publications (refereed papers)
  - Patents and licenses
  - Citations
- Transitions
  - BA 1 to BA 2 transitions
  - Transition to Innovative Naval Prototype and Future Naval Capability
  - Transition to program offices
- People
  - STEM program
  - Advanced degrees completed
  - Participants joining naval warfare labs

Qualitative measures could be established by assessing performance in each of these areas as good, fair, or poor. The resulting template is shown in Table 3-3.

TABLE 3-3 Metrics and Qualitative Measures of Effectiveness

	Measure of Effectiveness		
Metric	**Good**	**Fair**	**Poor**
Knowledge	Many publications, patents, citations	Some publications, patents, citations	Few publications, patents, citations
Transitions	Many transitions 6.1 to 6.2, INP, FNC	Some transitions 6.1 to 6.2, INP, FNC	Few transitions 6.1 to 6.2, INP, FNC
People	Many STEM students, advanced degrees supported, NWC/ Laboratory hires	Some STEM students, advanced degrees supported, NWC/ Laboratory hires	Few STEM students, advanced degrees supported, NWC/ Laboratory hires

NOTE: FNC = Future Naval Capabilities; INP = Innovative Naval Prototype; NWC = Naval Warfare Centers.

Parsing such quantified measures of effectiveness at too low a level (e.g., individual Warfare Center, specific S&T area) can be misleading. However, when they are aggregated at a higher level, the results are meaningful as a health assessment summary, despite the fact that the metrics reported by the NNR-NE are primarily “lagging” as opposed to “leading” metrics, which in general require long dwell times before results can be measured and reported.

As a means to improve on measuring outcomes and evaluating results for NNR-NE, the committee-commissioned paper on transitioning technology to naval ships provides seven recommendations for improving S&T technology transition in general based on lessons learned from case studies (Doerry 2010). The recommendations are to

- Use product lines and associated technology development road maps,
- Use more robust metrics,
- Improve technology transition agreements,
- Fully implement technology interpreters (termed “relationships managers” in the paper),
- Modify the DOD financial management regulation (DODFMR) to include technology transition activities in BA 3,
- Modify the DODFMR to split BA 4 into product line development and advanced component development and prototypes, and

- Assign the Office of the Chief of Naval Operations N091 as the resource sponsor for product line development in addition to S&T.

While many of these recommendations have direct application to higher levels of S&T funding than those considered in the committee's task statement (e.g., BA 3 and BA 4), there is a clear opportunity to improve NNR-NE BA 1 and BA 2 outcomes. The committee assessed these recommendations in the context and scope of the NNR-NE and identified two recommendations that can produce metrics that are better leading indicators of NNR-NE program efficacy–the effectiveness of technology interpreters and of product lines and associated technology development road maps. In the previous section, the value of the technology interpreter concept in improving communications between naval communities was presented. Simply implementing (or measuring the frequency of) meetings with participants from multiple departments or divisions can serve as an indicator as to whether the communities are collaborating, which will help the program officer in making better-informed decisions.

Application of the recommendation to promote the use of product lines and associated technology development road maps can also produce metrics that are leading indicators of NNR-NE program efficacy. As noted in the commissioned paper:

> The current model favoring transitioning technology directly from S&T to products directly supporting acquisition programs has lead to the R&D "Valley of Death." The principal cause of the "Valley of Death" is that a ship acquisition program has a very short window following Milestone A to fund technology development that will mature in time to support integration into the overall ship design process. Technology that is not perceived to be ready during this short window will typically not be incorporated. Unfortunately, without a ship acquisition program supporting the technology development, the technology may not receive sufficient support and funding to be ready for the next ship design opportunity as well. (Doerry 2010, 56)

The paper further observes:

> Transitioning to a Product Line approach is more likely to result in technology being ready for product development when specific ship acquisition programs need them. In a product line approach, BA-4 programs partner with BA-3 S&T efforts to mitigate technical risks and build the industrial capability to produce a product meeting the ship acquisition needs quickly and

> affordably. While BA-3 efforts concentrate on achieving a TRL [Technology Readiness Level] level 5, BA-4 Product Line programs concentrate on achieving an EMRL [Engineering and Manufacturing Readiness Level] 3. A significant advantage of using a Product Line Approach is that technologies are much more mature when incorporated into acquisition programs. . . . employing mature technologies has shown on average to significantly reduce RDT&E Cost Growth. Technology Development Roadmaps are excellent tools for keeping the Resource Sponsor, Science and Technology Community, Acquisition & Engineering Community, and Industry working towards a common vision. The development and promulgation of this shared vision is an important element of transitioning knowledge among the communities. (Doerry 2010, 56)

MAINTAINING CONNECTIONS ACROSS THE WIDER NAVAL ENGINEERING COMMUNITY

Maintaining connections across the wider naval engineering community is a key requirement for NNR-NE activities, given the small size of the community and its technical specialization. Two types of activities are important: those focused on bridging gaps between communities or disciplines in the naval engineering community and those focused on enabling people within or connected with the naval engineering community to perform effectively. The committee considered both types of activities in its assessment.

Bridging the Valleys Between Communities

Maintaining connections across the wider naval ship engineering community means bridging the valleys that naturally exist between the naval research, design, manufacturing, and operational communities and commercial and offshore communities. While these communities share a bond relating to the environments in which they operate, to the systems that they build, and to the manner in which they are deployed, there is an innate separation stemming from rules, regulations, cultures, values, motivations, and behaviors. For example, the professional literature related to technology transfer is replete with discussions of the “valley of death” (NRC 2004).

Sustaining an adequate naval engineering pipeline and achieving the twin goals of developing human capital and revitalizing naval ship systems engineering require a focus on ensuring effective connections among the elements of the wider naval engineering community. That broad community consists of universities, industry (e.g., shipbuilders, mission system integrators, vendors), Department of the Navy research centers (e.g., NSWC-CD, NUWC-ND), DOD activities (e.g., DOD Ship High Performance Computing Modernization Office, DARPA), private research institutions (e.g., SAIC, APS), classification societies (e.g., the American Bureau of Shipping, Lloyds) and professional societies [e.g., the Society of Naval Architects and Marine Engineers (SNAME), the American Society of Naval Engineers (ASNE)], naval activities (e.g., NAVSEA, ONR), and the fleet (e.g., the Navy Warfare Development Command). A 2002 NRC study of alternative approaches for organizing cooperative research addressed various options available to ONR for strengthening its naval engineering cooperative research programs (TRB 2002). To make the task more manageable and to focus on the core strategies to conduct cooperative research programs, the 2002 NRC committee described and evaluated a small number of underlying organizational models:

- An individual principal investigator model,
- A professional society–community of practitioners model,
- A consortium or center model, and
- A project-centered model.

The 2002 committee used the features of each model to assess each relative to goals for improved organization and management, research, education, and technology transfer. That committee found that each model had features making it unique and independent of the others, although there were common threads among the models in terms of project management, research theme selection, use of peer-review processes, processes to engage stakeholders, and use of councils and committees to make recommendations and decisions. The 2002 committee also found that there were advantages to hybrids or mixes of the above models under which practices typical of one model were embedded in the operation of another. The committee suggested that a sound strategy would be to include a major project in either the professional society–community of practice model or the consortium model. Table 3-4 summarizes the capacity of each of the models to meet the NNR-NE stated objectives as assessed by the 2002 NRC committee (TRB 2002).

TABLE 3-4 Summary of Cooperative Research Organizational Models and How Well They Meet Objectives

	Model			
Objective	**Baseline**	**Professional Society**	**Consortium**	**Project-Centered**
Human capital				
Attract students	Medium	High	High	Medium
Retain and attract new faculty	Medium	Medium	High	Medium
Provide continuing education	Low	High	High	Medium
Foster total ship engineers	Low	High	High	Medium
Naval engineering design				
Create new research opportunities	Low	Medium	High	Medium
Promote innovation	High	Medium	High	High
Ensure research useful to ship design	Low	Medium	High	High

Source: TRB 2002.

The 2002 report found that all three models for cooperative research organizations that it evaluated were capable of meeting all of ONR's program objectives. With regard to the ability to meet human capital and naval engineering and design objectives, the consortium model was found better than the professional society model, but both were significantly better than the project-centered model. The 2002 NRC committee, however, suggested that the absolute ranking of these models should depend on the relative importance given by sponsors to each objective.

Several cooperative research models have strengths that would be useful in meeting NNR-NE objectives. Specifically, the consortium and project-centered models can encourage innovative and integrative research through their inherent structures, since they involve a high degree of stakeholder participation and therefore have a high probability of meeting Navy needs.

The 2002 NRC committee identified strengths of each of the three cooperative research models. The professional society–community of practice model was found to excel in meeting the need to develop human capital. It is particularly strong in attracting and retaining students, supporting continuing education and training programs, and fostering the education and development of total ship engineers, which are principal missions of professional societies. The consortium model has characteristics that are well suited to meeting human capital development and naval engineering design objectives for cooperative research programs. However, its success in meeting these objectives will be principally determined by the leadership of the consortium and its ability to represent and balance the needs of the various stakeholders. Finally, the project-centered model has the potential to excel in promoting innovation in naval engineering design and in promoting research that is useful to ship design and production. This strength is based on the strong, large-scale, interdisciplinary project focus inherent in the model, which includes participation and encourages collaboration of the key stakeholders (TRB 2002).

Total ship engineers are developed through a combination of a formal total ship design curriculum and hands-on design experience in multidisciplinary projects. Regardless of the model selected, the ability to foster development of total ship engineers depends on the opportunities for attainment of the necessary formal education and design experience.

Enabling People

A critical aspect of developing human capital and revitalizing the naval ship systems engineering community is enabling the people who make up that community. Enabling naval engineers includes the following tasks, as defined by NAVSEA at the committee's January 2010 workshop (see Appendix A) (H. Stefanyshyn-Piper, presentation to the committee, Jan. 13, 2010):

- Providing naval engineering education;
- Providing naval engineering training to keep the workforce up to date;
- Providing naval engineering mentoring in and outside the workplace, including activities with and through professional technical societies;
- Developing tools and collecting supporting data and supporting verification, validation, and accreditation activities;
- Developing ship design processes, including those for continuous process improvement and technology transition; and

- Developing documentation, including specifications, standards, handbooks, and rules.

Specific needs with respect to developing human capital and revitalizing systems engineering are described in the following section.

Conclusion: Connectivity, communication, and human resource and organizational development are important to the success of the naval engineering enterprise. However, the committee was unable to find evidence that NNR-NE strategic research planning makes use of measures of connectivity, communication effectiveness, or human capital or organizational development.

Recommendation: ONR's enterprisewide strategic planning and assessment process for NNR-NE should include the following:

- A process to develop NNR-NE strategic priorities with respect to connectivity with the wider naval engineering community as well as with respect to communication with stakeholders, technical advisory groups, the user community, and the broader research community. The process should include adoption of one or more of the cooperative research models reviewed in the report of the 2002 NRC Committee on Options for Naval Engineering Cooperative Research;
- A process to identify NNR-NE priorities associated with human capital and organizational development; and
- Metrics associated with connectivity with the naval engineering community and human capital and organizational development.

Recommendation: To maintain connectivity across the wider naval engineering community, NNR-NE should utilize the concept of technology interpreter and should continue to support, participate in, and incentivize its ongoing connectivity and communication activities, including conferences, workshops, and seminars, and the activities of ONR Global. ONR should consider adopting additional connectivity and communication activities, including brown bag seminars, scholarly exchange events, and rotation and refreshment opportunities for NNR-NE program officers. The latter should include research sabbaticals at

Navy laboratories and academic research institutions and in operational Navy settings.

INTEGRATING NAVAL ENGINEERING S&T

As discussed earlier, the committee suggests that ONR needs to take additional steps to enhance its organizational and management practices in setting performance goals and evaluating results. This is especially critical for research organizations such as ONR with significant multidisciplinary programs and related challenges.

The committee found several examples of interdisciplinary and integrative research in the NNR-NE portfolio. In its commissioned papers and workshops, the committee found additional evidence of integrative and interdisciplinary naval engineering projects such as the integrated composite mast (Hackett 2010), and it found a number of materials, hydrodynamics, and ship structures programs. However, the committee concluded that these projects resulted from the efforts of individual program officers or industry representatives who, for personal or professional reasons, engaged in interdisciplinary research and played a key role in developing such programs, rather than being an outgrowth of systematic ONR processes that fostered interdisciplinary or integrative research.

> **Recommendation:** As part of its enterprisewide strategic planning process, ONR should establish a culture of interdisciplinary and integrative research within and around the NNR-NE S&T enterprise and should establish processes that foster, encourage, and incentivize interdisciplinary or integrative research. The NNR-NE interdisciplinary and integrative research objectives should be established as part of the strategic planning processes and should include assessment, benchmarking, and continuous process improvement components.

DEVELOPING HUMAN CAPITAL AND REVITALIZING NAVAL SHIP SYSTEMS ENGINEERING

The 1990s were a period of great change within DOD and the Department of the Navy precipitated by the fall of the former Soviet Union, the end of the cold war, and the desire to capitalize on the so-called "peace dividend." One result was a substantial downsizing of the Navy organizations previously responsible for ship design and acquisition, accompanied by the outsourcing of these services to industry. According to the General Accounting Office, "DoD performed this downsizing [from 1989 to 2002] without proactively shaping the civilian workforce to ensure that it had the specific skills and competencies needed to accomplish future DoD missions" (GAO 2004, 7).

During that decade, the Department of the Navy in general and NAVSEA in particular saw a deep reduction in the human capital required to design, develop, acquire, deploy, and maintain the naval fleet. NAVSEA headquarters alone saw the cadre of highly experienced naval ship design engineers shrink from about 1,200 in 1992 to fewer than 300 in 2005 (Keane et al. 2009, 47). Concerns related to the naval acquisition workforce were articulated by then Secretary of the Navy Donald Winter in a 2007 speech before the Navy League: "There has been a steady erosion in domain knowledge within the Department of the Navy over the past several decades, resulting in an overreliance on contractors in the performance of core in-house functions" (Winter 2007). Secretary Winter went on to say that while "the Department's level of technical expertise associated with naval architecture and design is relatively high, our knowledge of the shipbuilding process is short of what it has been in the past, and what it needs to be in the future. Our challenge is to understand how to integrate design and production technology into an acquisition process that industry can execute. This requires a deep knowledge of systems engineering and a profound understanding of the acquisition process. Systems engineering is key to ensuring that each ship is configured to optimize the fleet" (Winter 2007).

Secretary Winter discussed the steps necessary to correct the deficiencies in naval ship acquisition, and the workforce in particular, saying that "the Navy needs to provide knowledgeable program oversight. Hiring top-quality people who have experience with large shipbuilding programs is essential. The ability to assign an experienced and capable team must be a precondition to a program's initiation. Finding and developing the people we need is easier said than done, and it will take time to rectify this problem, but we cannot ignore the leverage that can be obtained by putting the right, experienced and prepared people, in the right positions" (Winter 2007).

The need to develop the requisite human capital and revitalize naval ship systems engineering has been clearly recognized by the Navy leadership as a key goal. Today, efforts exist not only to protect and maintain the mission-critical competency areas but also to develop them for the present and future. The development and monitoring of the health of naval engineering human capital have been actively pursued within NAVSEA by using tools such as the Human Capital Digital Dashboard (Tropiano 2005), which provides an objective assessment of the following:

- Alignment of engineers with the technical authority chain of command;
- Availability and adequacy of technical documentation, including specifications, standards, tools, and processes;
- Workforce demographics, including age and levels of education;
- Workforce skills, including experience, certifications, and other special abilities;
- Workforce health metrics, including assessments of leadership skills, mission capability, and technical documentation;
- Problem areas, such as critical vacancies, anticipated retirements, and substandard assessments; and
- Long-term health actions in these areas.

Developing the Navy's next generation of naval engineering leaders is a challenging problem. During the 1990s, as a result of changes in acquisition policy, preliminary and contract design for Navy ships that NAVSEA had previously performed in-house began to be contracted out to shipbuilders. In addition, the rate of new ship acquisition declined in this period compared with that of the previous decade. The contraction of the NAVSEA headquarters ship design staff noted above was a consequence. This problem is being addressed on several fronts. One initiative was the creation of the Center for Innovation in Ship Design (CISD) in 2002 by NAVSEA, ONR, and NSWC. CISD was tasked in 2006 "to develop a Human Capital Strategy (HCS) for Ship Design Acquisition Workforce Improvement. The Ship Design Management HCS will ensure a highly experienced warship design workforce to sustain NAVSEA as the nation's leader in naval ship design" (Keane et al. 2009, 46). The committee noted that this focused program has in large part sustained the core competencies that are essential to rebuilding the naval ship systems engineering and acquisition workforce.

The need to train, develop, and refresh the naval ship systems engineering workforce and technology base continuously was articulated in previous studies (NRC 2000; TRB 2002; U.S. Department of Commerce 2001). It was widely discussed in the naval engineering professional journals (ASNE 1992) and in academic settings (Chryssostomidis et al. 2000). These writings served to identify the "failure of government and industry research and development (R&D) organizations to stimulate the education, innovation, and competitiveness improvements needed to support the U.S. shipbuilding industry. These reports highlight the significant role the Department of Defense must play in leading the R&D investment stimulus for the cooperative development of innovative, cost and labor saving technologies by the U.S. shipbuilding industry and the supporting academic institutions. Additionally, each subsequent report has continued to identify the areas of education, innovation and competitiveness as problematic in the U.S. shipbuilding industry" (ONR 2001, 1–2).

The naval engineering human capital pipeline is illustrated in Figure 3-1. The pipeline begins with the kindergarten through 12th grade (K-12) pool of STEM students. Those high school students who enter universities and colleges and graduate with a bachelor of science degree will enter the general engineering workforce in the tens of thousands annually, while thousands will continue on for advanced degrees. Each year, no more than a few thousand new graduates (and in some years probably less than a thousand) at all degree levels will enter the naval engineering enterprise workforce. Of those graduates who do enter naval engineering, a small number each year will leave the workforce to pursue a higher degree, motivated by their experience in naval engineering. A select few will stay on in academia to educate the next generation of naval engineers. The ever-present demand signal for graduates is driven by the natural progression of scientists and engineers in their careers and eventual attrition from the workforce either through a career change or retirement. Supporting this pipeline for the development of naval engineers is the infrastructure of primary and secondary schools, colleges and universities, government research activities, private-sector research

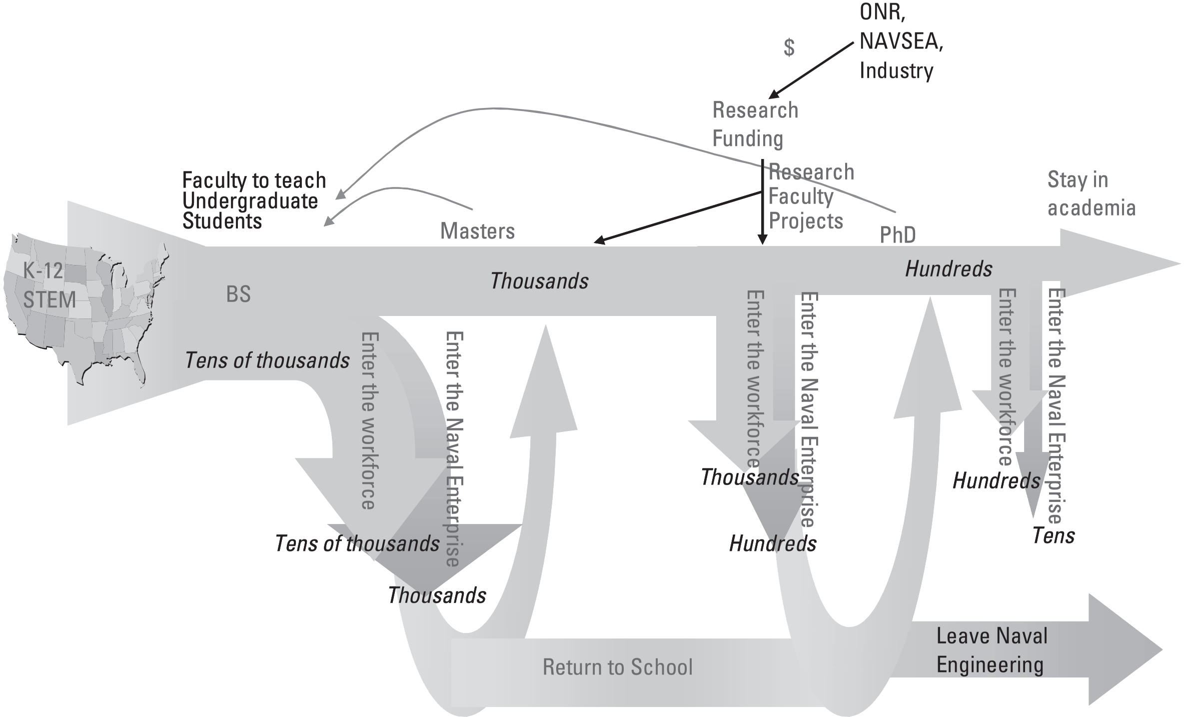

FIGURE 3-1 **Naval engineering value stream and pipeline.** (SOURCE: National Shipbuilding Research Program 2009. Printed with permission from the National Shipbuilding Research Program, from the Shipbuilding Engineering Education Consortium Viability and Operational Concepts Final Report, June 16, 2009.)

institutions, and university research centers. The National Shipbuilding Research Consortium's 2009 study of the naval engineering workforce, conducted for NAVSEA, concluded that the demand for hiring of entry-level naval engineers by NAVSEA, U.S. shipbuilders, and the supporting industries is about 2,000 per year, while graduates of accredited programs of naval engineering total only about 200 annually (National Shipbuilding Research Program 2009, 30). This demand estimate appears inconsistent with the report's estimate of total employment of naval engineers in these sectors of 15,000 (National Shipbuilding Research Program 2009, 21). Any excess of demand over supply must be filled by hiring and training engineers from other specializations.

Developing a robust naval engineering pipeline is critical to the development of a robust naval engineering enterprise. NNR-NE efforts in naval engineering S&T workforce development have been sporadic and inadequately supported to date. ONR has been designated the lead agency for STEM efforts for the Department of the Navy; however, such responsibilities are considered an ancillary rather than a core functional responsibility.

Outreach programs have been successful in reaching students and creating an interest in STEM education and potential naval and maritime careers. ONR supports SNAME efforts to deploy the SeaPerch program nationally and to develop ways to expand and enhance the promotion as part of ONR's NNR-NE outreach. Professional technical societies such as SNAME and ASNE appear to be well positioned to provided leadership and support for these outreach initiatives. However, limitations do exist in the professional societies' ability to perform this outreach given their modest number of volunteers and funding for professional staff in relation to the broad K-12 population.

Recommendation: ONR should reinvigorate its efforts in developing the 21st century naval engineering workforce, including improvement of outreach activities to underrepresented groups. ONR's lead role for STEM activities should be strengthened and incorporated into its enterprisewide strategic planning processes, and performance metrics for workforce development and STEM achievements should be identified, measured, incentivized, and included in ONR's assessment, benchmarking, and continuous process improvement activities.

ONR should consider additional approaches to increase the efficacy of the workforce development and STEM initiatives, including the following:

- Targeting specific populations in a geographic region with professional connection to naval engineering activities (e.g., local naval architecture university, shipbuilder, naval facility);
- Expanding funding and volunteer support for outreach programs though collaborative efforts between government activities, industry, and professional societies (e.g., the Junior Engineering Technical Society); and
- Leveraging NAVSEA funding under the Naval Engineering Education Center Consortium to support SeaPerch and other initiatives.

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Abbreviations

AFOSR	Air Force Office of Scientific Research
ASNE	American Society of Naval Engineers
DHS	Department of Homeland Security
DON	Department of the Navy
GAO	General Accounting Office *or* Government Accountability Office
NRC	National Research Council
NSF	National Science Foundation
ONR	Office of Naval Research
TRB	Transportation Research Board

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4

Results and Future Prospects of the National Naval Responsibility for Naval Engineering

The task statement for this study asks the committee to "evaluate the current state of science and technology [S&T]—specifically, basic and early applied research—activities in naval engineering and closely related disciplines in the United States in the context of research, education (the 'pipeline' of future naval researchers, graduate and post doctoral), and the associated infrastructure. . . . [and to] report on the health of the basic and early applied research, graduate and postgraduate research 'pipeline' and the associated infrastructure necessary for a long-term, sustainable portfolio that will provide technology options for future Navy advanced technology development programs." In response to this charge, the first section below assesses the health of basic and early applied research, graduate and postdoctoral education, and the research infrastructure.

The task statement also asks the committee to assess the National Naval Responsibility for Naval Engineering's (NNR-NE's) "progress in the ability to: (l) provide and sustain robust research expertise in the United States working on long-term problems of importance to the Department of the Navy; (2) ensure that an adequate pipeline of new researchers, engineers, and faculty continues; and (3) ensure that ONR [the Office of Naval Research] can continue to provide superior S&T in naval architecture and marine engineering." In response, the second section of this chapter compares ONR activities and accomplishments with the original NNR-NE goals and assesses ONR's ability to fulfill the NNR-NE.

HEALTH OF THE S&T ENTERPRISE SUPPORTING NAVAL ENGINEERING

This section presents the committee's assessment of the state of health of the scientific and technical disciplines on which naval engineering depends most directly. The assessment examines the state of research in each field and the contributions of government laboratories, universities, and industry to the naval engineering S&T enterprise. The section also proposes how ONR could measure the health of these disciplines in a systematic way in the future to fulfill the NNR-NE mission.

The committee defined the health of research in a field in terms of the three kinds of research outputs intended from ONR's S&T investments (ONR 2009, 4): knowledge (evidence that the activity is a source of new understanding of physical phenomena and technologies relevant to naval engineering), transitions (evidence that research output leads to applications that strengthen naval capabilities), and people (evidence that the activity contributes to the pool of research talent and expertise devoted to naval engineering problems). A healthy research field was defined as one that is productive in advancing fundamental knowledge, has strong linkages to engineering practice as evidenced by the transition of discoveries to applications and by the existence of effective channels of communication between researchers and practitioners, and has positive future prospects as evidenced by the development and retention of talented researchers and by the attraction of new researchers and resources into the field. Typically, in a healthy research field, diverse topics are under investigation, a balance of research methods is being used, and resources are sufficient to allow ample opportunity for creative research and for pursuing transition opportunities. The ultimate success of research depends on the availability of practitioners who are aware of the latest scientific developments, are proficient in the latest techniques, and maintain close communication with the research community.

The state of the institutions conducting research in support of naval engineering is described in the first subsection below, and the state of research in the naval engineering–related S&T fields is described in the second subsection. The present study is not the first to consider the health of the naval engineering S&T enterprise; earlier assessments are summarized and commented on in Annex 4-2.

Research Institutions

The major participants in research supporting naval engineering are government laboratories (especially the Navy laboratories), universities, and the shipbuilding industry.

Navy Laboratories and Related Government Research and Development Facilities

The ability of the naval laboratories and other government research and development facilities to support the naval ship systems engineering S&T infrastructure was explored at the committee's January 2010 workshop (see Appendix A) and through analysis of the ONR portfolio of sponsored basic and applied research projects in the NNR-NE fields. At the workshop, representatives of the principal Department of Defense (DOD) and other government entities supporting naval ship systems engineering[1] were asked to discuss the following questions:

- What research is your institution supporting, or has it supported, that directly relates to the areas of interest of the Ship Systems and Engineering Research Division of ONR (hydromechanics and hull design; ship design tools; propulsors; ship structures; and automation, control, and system integration)?
- How did the research topics in these areas originate in your institution?
- Who has performed the research (e.g., internal laboratory personnel, external contractors, recipients of university grants, or multiple institutions in collaboration)?
- Has your institution cooperated with ONR for these research projects?
- Do you foresee research topics that would benefit from ONR coordination and support?

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[1] The Naval Surface Warfare Center, Carderock Division; the Naval Undersea Warfare Center, Newport Division; the Naval Research Laboratory; the CREATE Ship High Performance Computing Modernization Program; and the National Science Foundation.

The ability of the naval laboratories and government research and development facilities to support the naval ship systems engineering S&T infrastructure is varied. The results of the committee's assessment indicate the following:

- The Naval Sea System Command's (NAVSEA's) Naval Surface Warfare Center, Carderock (NSWC-CD), is the primary facility conducting research and development for transitioning NNR-NE research results to naval applications.
- NSWC-CD has been effective in supporting advanced degrees in naval engineering; in recruiting naval engineers; and in promoting science, technology, engineering, and mathematics (STEM) education.
- NAVSEA's Naval Undersea Weapons Center has relevant but limited activity in the NNR-NE areas, in particular, in unmanned vehicles and in system integration (focused on energy sources).
- The Naval Research Laboratory's diverse mission does not emphasize investments in the NNR-NE areas.
- Although the National Science Foundation (NSF) sponsors basic research in related areas (including fluid dynamics, structural materials, energy and power, and systems engineering), NSF-sponsored projects in these areas are heterogeneous and rarely address the problems critical to naval engineering progress. Similarly, the Defense Advanced Research Projects Agency (DARPA) and other DOD agencies support relevant research, but rarely with potential naval applications or specific Navy needs in mind.

University Research Centers and Private-Sector Research Institutions

The January 2010 workshop also explored the ability of university and private-sector research institutions to support naval ship systems engineering S&T. Representatives of university research centers, large and small private-sector research institutions, and naval shipbuilder research centers closely aligned with naval ship systems engineering were asked to do the following:

- Briefly outline the institution's involvement in basic and applied research and advanced technology development related to the areas of interest to the Ship Systems and Engineering Research Division of ONR (hydromechanics and hull design; ship design tools; propulsors; ship structures; and automation, control, and system integration). Features to describe include major interest areas and projects, departments involved, major sponsors and annual support (in round numbers), and numbers of faculty and graduate students.

- Characterize the overall health of the field in the institution's most active areas, for example, trends in funding, faculty, students, and significant recent research and development accomplishments.
- Identify opportunities for ONR to sustain research and education in these research areas.
- For the institution's most active areas, identify the factors that drive the research and development agenda. How does the institution plan for future growth or contraction in these areas? How do the institution's researchers interact with users of research (beyond the funding source)? What role does ONR have in setting the agenda in this field?

The results of the committee's assessment indicate the following:

- Considerable university research is funded by the Navy in hydrodynamics, hydromechanics, and advanced hull design areas. Several universities have towing tanks to conduct experimental research.
- Research in the naval engineering S&T areas conducted by private research institutions and shipbuilders is funded by the Navy. There is little or no commercial funding of naval engineering research at universities and private research institutions.
- Design agents support shipbuilders or the Navy in design-related activities. Some design agents develop ship design tools to assist their design-related activities.
- Providing scholarships to junior- or senior-year undergraduate engineering students to encourage them to pursue a naval engineering focus probably would be effective in increasing the engineering workforce supply.
- The Navy is essentially the sole source of academic research funding in the areas of naval hydrodynamics and naval ship design, and university research in these areas would cease without this support.

Commercial Shipbuilding, Offshore Petroleum Industry, and Professional Societies

The ability of the commercial shipbuilding industry, the offshore industry, and classification and professional societies to support the naval ship systems engineering S&T infrastructure was explored at the January 2010 workshop and through analysis of case studies (Hackett 2010; Hagan 2010; B. J. Carter, presentation to the committee, Jan. 13, 2010). Representatives of commercial shipbuilders, the offshore industry, and classification and professional societies[2] were asked to give information similar to that asked of the university and private research institutions.

The information received from these sources indicates the following:

- Investment in commercial ship systems engineering technology within the United States is limited. Therefore, the Navy cannot rely on the commercial industry to sustain the naval ship system engineering S&T infrastructure and technology base. However, some U.S. shipyards have developed relationships with foreign shipyards, which have resulted in application of commercial ship construction concepts developed abroad to Navy shipbuilding programs (B. J. Carter, presentation to the committee, Jan. 13, 2010).
- Commercial shipbuilding is focused on efficiency and cost, which are of interest to the Navy.
- There is a healthy investment in offshore technology that is vital in supporting and sustaining the maritime-related university infrastructure and the naval engineering human capital pipeline for this segment of the industry.
- Classification societies' research is primarily focused on supporting classification rules or standards development for commercial ships and other marine structures.
- Professional societies such as the Society of Naval Architects and Marine Engineers support educational programs and have technical and research committees that address some of the S&T activities.

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[2] General Dynamics National Steel and Shipbuilding Company (NASSCO); Herbert Engineering Corp. Group; ConocoPhillips; Chevron; American Bureau of Shipping; and Maersk Maritime Technology, AP Moller-Maersk.

- The activity of the international research community in shipbuilding countries such as Japan, Korea, China, and Norway (a center of the offshore industry) is isolated from U.S. interests and efforts.
- Alternative approaches to improving the efficacy of these activities would include increasing government investment in the U.S. commercial S&T infrastructure and promoting government–industry cooperative research and development of dual-use (commercial and naval) technology.

State of Naval Engineering Research Institutions: Summary Observations

The naval engineering S&T enterprise relies on government support. Therefore, the national laboratories, university research centers, and private-sector research centers tend to conduct project-based research in highly specific areas. The unique attributes of naval ship design limit the ability to make wide use of technology imported from other disciplines; therefore, the responsibility for S&T advances in this industry rests on the industry customer. Thus, government has no option other than to invest directly in the S&T enterprise to advance the naval engineering industry and to keep national efforts current with world developments.

In the United States, there is little transfer of technology from the commercial shipping industry to the naval engineering industry, in part because of the differing forces that drive the two industries. While each industry is concerned with the design, production, maintenance, and operation of ships, the driving force in commercial shipping is one of minimizing cost. Minimizing total ownership cost is growing in importance for the Navy, but this focus is tempered in naval engineering because of the many constraints and requirements that determine naval ship design. Therefore, the commercial ship design industry is not a major contributor to efforts to advance naval ship design S&T. Clear exceptions are in the areas of ship design for producibility and ship production methods, where commercial technology and practices are important contributors to improvements in naval ship manufacturing and reductions in ship acquisition cost. There has also been appreciable commercial technology transition in maintenance and in crew size issues associated with automation and control.

Research in the S&T Areas Supporting Naval Engineering

The committee's sources of information on the current state of research in the S&T areas supporting naval engineering (hydromechanics and hull design; propulsors; structural systems; ship design tools; automation, control, and system integration; and platform power and energy) included the January 2010 workshop described in the preceding section, certain of the papers commissioned by the committee (Triantafyllou 2010; Kiss 2010), and the June 2010 workshop at which researchers supported by ONR discussed the prospects for contributions to naval engineering from research in their fields (see Appendix A). Each of the June workshop researcher panelists, as well as other researchers who did not attend, responded to the following questions relating to the state of health of the panelist's field:

- How would you characterize the overall health of your field? Have there been recent breakthrough accomplishments in the field? Are the trends positive in your field for attracting researchers and funding?
- Are advances in your field tied to other fields of research? What are the links, and how do the dependencies among the fields affect research in your field?
- Where does financial support for research in your field come from, in the United States and internationally?
- What are the most significant areas of challenge in your field of research in the next 20 years? What are the hard problems in your field? What are the obstacles to progress in your field?

Hydrodynamics and Hull Design; Propulsors

The major supporters of hydrodynamics basic research in the United States historically have been the Navy, NSF, and the National Aeronautics and Space Administration (NASA). NSF supports a diverse and substantial program of basic and applied research in fluid mechanics, including projects that have potential applications ranging from chemical engineering to robotics and medicine, but few address hydrodynamics problems of likely relevance to naval engineering.

The field of naval hydromechanics, that is, research aimed at understanding the physical phenomena that determine the hydrodynamic and hydroacoustic performance of naval ships, arguably would not survive without Navy support. The move in recent years to replace experimental work with computation—in part to save costs (and time)—has not yet achieved the ultimate potential savings and has in fact created new demands for experimentation and measurements to provide the necessary validation and calibration of codes and models. Given current resources and objectives, the current mix and balance of U.S. naval hydrodynamics basic research (primarily, the ONR program) may be the best that can be achieved to meet narrowly focused needs. However, the overall program is stretched thin and is not robust enough to meet unanticipated critical Navy needs. More important, it does not have sufficient depth in more basic investigations to generate the breakthrough and disruptive technologies that could redefine naval engineering in the future.

The balance between computational and experimental work in hydrodynamics must be carefully monitored. Experimental validation remains an essential step in the development of hydrodynamic models. However, experiments are costly and therefore more vulnerable during periods of budget pressure. Experimental facilities depend on funded research for their support and will deteriorate without use. Major research facilities are maintained and used at NSWC-CD and elsewhere, primarily at universities.

Structural Systems

U.S. industry supports little naval structures research because few large commercial ships are built in the United States. Naval structures research is performed and funded in the commercial sector in such countries as Japan and Korea, where commercial shipbuilding is a major industry. Basic research in structures and structural materials (that is, research not focused on naval applications) has a broad range of potential applications and receives support from multiple public sources (including NSF and NASA) as well as private-sector sources; therefore, many structures researchers are working in the United States who could perform naval structures research if they received funding from ONR. However, the health of the field of structures research directly related to naval engineering, exclusive of ONR activities, can only be considered as poor to fair in the United States.

Ship Design Tools

There is little research in the United States aimed at developing improved tools and methods for use in the early stages of the design of new naval ships. In the early design stages (e.g., feasibility studies, preliminary design, contract design), the performance requirements for the new ship must be translated into a viable design concept (or alternative concepts), and the design is defined up to the level of detail required for making cost and construction schedule estimates (contract design). These early design phases use specialized methods and models such as ship synthesis tools, set-based design methods, physics-based performance prediction models, and cost-estimating tools. Decisions made at the early design stages determine the basic architecture of the ship and ship systems and costs of construction and ownership (Keane 2011, 13).

A recent analysis of Navy ship design capability concluded that "overall, the availability and quality of analysis software has eroded with the passage of time. There has been inadequate investment to keep pace with changes in computer technology, weapon systems technology and ship technology (materials, hull configurations, power density, etc.)" (Billingsley 2010, 6). It has been estimated that the lack of robust physics-based tools for use in early design in recent Navy surface combat ship programs has resulted in added costs on the order of hundreds of millions of dollars to the Navy for repair of material deficiencies that have arisen in service and has placed operational restrictions on the ships' deployment (Keane 2011, 10–12).

At the same time, the shipbuilding industry, with Navy support, has invested significantly in development of tools for detail design, the stage of design that produces the plans and procedures that guide the shipyard construction workers and provides control over construction cost and schedule. These shipyard design tools are more advanced than those in use for commercial ship design and construction, because the technical complexity of modern naval ships demands more sophisticated methods.

The advanced shipyard design tools have potential uses throughout all stages of design. Some recent acquisition programs, notably the Virginia Class submarine program, have applied integrated product and process development (Figure 4-1), an approach to ship design and construction in which the early design stages are integrated with construction planning

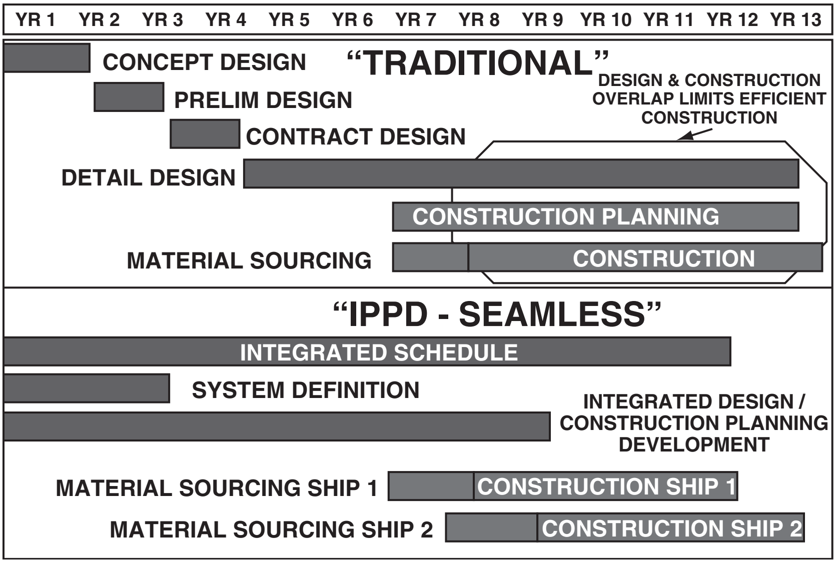

FIGURE 4-1 **Traditional versus integrated product and process development ship design and construction processes.** (IPPD = integrated product and process development. SOURCE: General Dynamics Electric Boat 2002, 28.)

to improve the efficiency with which performance and cost objectives are met (General Dynamics Electric Boat 2002; Keane et al. 2005, 4, 9). In the Virginia Class program, product and process designs were integrated through a central model and a database provided by the shipyard. However, broader use of shipyard design tools and databases in this manner may be hindered because there has been little transition of the technology developed by the private-sector shipyards to Navy ship designers, many advances are regarded as proprietary, and the level of detail in associated databases is often not compatible with the early-stage analysis of alternatives and set-based design for new concepts.

The NNR-NE portfolio does not include investments in detail design tools because development of these tools is not considered to be basic research. In general, research in ship design tools tends to be focused on the transition of basic research knowledge gained in multiple disciplines into design applications; hence, it is often perceived as applied research and may receive low priority in programs oriented toward basic research.

Nonetheless, there are basic research opportunities associated with generic technologies such as systems engineering, multidisciplinary optimization, set-based design, efficiency and accuracy of solvers, physics-based modeling, and multiphysics coupling techniques. These opportunities are particularly relevant for advanced ship concepts where there is often a lack of existing rules-based methods and experimental data and existing tools have not been verified, validated, or accredited for use. Because basic research on ship design tools has a limited range of potential applications and receives meager support from government or private-sector sources, few researchers in the United States are predisposed to perform such research even if increased funding were available from ONR.

The analysis of Navy design capabilities cited above noted shortcomings in ONR's record of developing applicable design tools: "ONR-sponsored software is frequently a by-product of research in disciplines of interest to ONR programs. These may or may not align with ship design needs. The user interface of research software is typically barely adequate for the needs of research scientists and can be incomprehensible to a ship design engineer. Additionally, much of the software developed under ONR grants ends up not belonging to the Navy. Lastly, research software rarely has the validation or assured range of applicability one would desire for acquisition design" (Billingsley 2010, 7).

Recognizing a need for increased investment in research on ship design tools, DOD has established the Computational Research and Engineering Acquisition Tools and Environments (CREATE) program to develop and deploy computational engineering tool sets for acquisition engineers. However, this effort is limited in scope compared with the breadth of disciplines involved in naval ship design and the depth (ranging from feasibility to detailed design to in-service support) to which they need to be addressed. In summary, the health of basic and early applied research relevant to naval ship design tools can only be considered as poor in the United States.

Looking to the domestic and international shipbuilding industry to supplement the development of naval ship design tools and methods has had mixed results. The U.S. domestic large commercial vessel market has declined over the past 40 years, while the inland lakes and rivers vessels market has remained fairly robust. The ship design tools developed for these segments of the industry have limited application to early-stage naval ship design and physics-based performance modeling, especially for the complex problem of designing and integrating mission systems with naval platforms. Nevertheless, many of the commercial-off-the-shelf (COTS) computer-aided design (CAD) tools for product geometry modeling, general-purpose finite element analysis, and so forth have found their way into ship design and have been customized for naval use. However, COTS can satisfy only a minority of naval ship design software needs because most naval ship design software needs are highly ship-specific (Billingsley 2010, 7). The complexity of naval ship design has made necessary a combination of COTS and design tools developed by the Navy and shipbuilders (Kassell et al. 2010, 8).

Ship design tools research is actively pursued in the commercial sector in Asia (where commercial design and shipbuilding are thriving competitive industries) and in Europe. The focus in these markets is on large product carriers, containerships, passenger ships, and offshore vessels and platforms and therefore has limited applicability and little opportunity for transition to naval combatant ship design. There is a somewhat active international naval design industry, which has produced tools with potential application to early-stage ship design. The products stemming from this enterprise (e.g., the commercially developed Paramarine integrated naval architecture software) are integrated CAD and engineering tools that support naval ship design. The Navy is exploring the utility of such tools from the perspective that a COTS package should be used if it has the required capability, can be reasonably integrated into the design process, and proves to be the most cost-effective solution (Kassell et al. 2010, 9).

Automation, Control, and System Integration

Research in automation and control is receiving significant support from NSF and DOD. Both agencies support basic research, and DOD is the major supporter of applied research. NASA has supported work in this area.

Basic and applied research in automation and control outside ONR appear to be strong, in terms of funding and numbers of researchers. In general, controls, embedded systems, and automation are relatively well-funded topics in engineering research today. These activities include research relevant to naval systems. The evident ONR niche in the field is application to specific Navy requirements (e.g., robotic underwater vehicles). System integration has fewer researchers but is funded by government agencies in addition to the Navy. As with automation and control, the principal Navy-specific problems appear to be application to special needs.

Platform Power and Energy

Power and energy technology is a dynamic field driven by developments in computing; telecommunications; and power electronics for industrial, consumer, and grid applications. Research and development in power systems is conducted and funded by industry, the Department of Energy, NSF, and DOD. DOD, and in particular the Navy, has been among the leaders in the funding of research to support the design of power systems of up to 100 MW capacity, matching Navy needs. Research on land-based systems can be expected to make a contribution to components and subsystem technologies that meet the Navy's special power system requirements. The Navy seeks to develop power and energy systems for ships that will be equipped with electric drives and with electrically powered weapons and high-power radars. Because future shipboard systems will be of small physical dimensions and have power demands far exceeding the available onboard generation, the problems and possibilities for ship-based power system control significantly differ from those for land-based systems. Each weapon and radar system will not be able to bring its own power system on board, and the future ship power system will be different from the ship system of the past. Ensuring efficient transition of new power and energy technology to the designers and builders of Navy ships is an urgent concern.

State of Research in the S&T Areas: Summary Observations

The committee's review revealed that some of the S&T areas within the scope of the NNR-NE initiative derive strength from a breadth of related applications. These fields benefit from a diversity of funding sources and opportunities for cross-fertilization among communities of researchers working under different sponsorship. For example, vibrant research communities are devoted to computational fluid dynamics and to structural materials and systems, fields of research that have broad application in engineering practice in many industries. In these fields, the tasks for the NNR-NE initiative are to ensure that the Navy takes full advantage of the broad pool of researchers that could contribute to solving its high-priority problems and to fund basic and applied research on problems relevant only to Navy applications. Mechanisms for this purpose may include better marketing of ONR support opportunities and establishment of more structured interactions with other sponsoring agencies.

In other NNR-NE fields or subfields (e.g., propulsors and naval hydrodynamics), ONR and other Navy agencies are nearly the only sources of support. If the Navy were to identify an urgent need to expand research related to naval problems in these fields, the pool of researchers qualified to work immediately on such problems and not already occupied with Navy-sponsored research would be small. The ONR responsibility for sustaining education and the institutional infrastructure in these fields is great. Because of the differences between NNR-NE disciplines, ONR activities to fulfill its NNR-NE obligations need to be tailored to the status of each individual field.

CONTRIBUTION OF ONR's NNR-NE

The committee assessed how ONR's programs support naval engineering S&T in two steps. First, it examined ONR's execution of the required elements of the NNR-NE initiative, as defined in the 2001 and 2010 memoranda guiding the NNRs: Has ONR carried out all the required activities in a meaningful way? What resources have been devoted to each?

Second, the committee examined the composition of ONR's portfolio of basic and applied naval engineering research. The research portfolio is ONR's primary means of ensuring scientific and technical innovation and therefore is at the heart of the NNR-NE. The committee asked whether this portfolio adequately supports the scientific and technical fields specified in the 2001 memorandum, whether it is of reasonable scale, and whether it appears to be appropriately balanced with respect to disciplines and between basic and applied topics. The committee used ONR's metrics for the S&T output of its basic and applied research, which include numbers of papers published, numbers of advanced degrees awarded to researchers receiving ONR support, and numbers of projects whose results make the transition to applications. The committee also considered alternative methods and metrics for evaluating the NNR-NE research portfolio.

Execution of the NNR-NE

The following subsections describe how ONR has executed each of the major activities specified in the 2001 memorandum and the 2010 instruction: investing in the key S&T areas; conducting major field experiments; investing in human capital and in S&T physical infrastructure; investing in STEM education; and conducting the functions of planning, periodic review, and external coordination.

Investing in Key S&T Areas

The investments in key S&T areas that the 2001 memorandum calls for occur through the grants and contracts that ONR regularly awards for basic and applied research. ONR considers supported research projects on specific topics that are administered by the Ship Systems and Engineering Research Division (ONR 331) to be within the NNR-NE. Investments in these key S&T areas are examined first from a funding perspective and then from a quality perspective.

Since 2001, ONR has redefined the technical areas within the NNR-NE. The 2001 memorandum directed that seven areas in naval engineering be considered to constitute the S&T breadth of the NNR-NE: ship design tools, ship structural materials, hydromechanics, advanced hull designs, ship propulsion, ship automation, and systems integration. The task statement for the committee's study refers to the same seven technical areas and instructs the committee to assess whether they adequately define the scope of NNR-NE. By 2010, ONR's definition, in the tabulations of NNR-NE research projects provided to the committee, had evolved to six areas, as presented in Table 4-1.

This definition differs from the list of seven key areas identified in the 2001 NNR-NE memorandum mainly in the explicit inclusion of platform power and energy in the current list. Annex 4-1 presents ONR's description of each field, including the objective of research in the field, important problems, the rationale for inclusion in NNR-NE as a Navy-unique technical issue, and the expected payoff from research in each field. Funding for 2006–2009 for each technical area, according to the 2010 NNR-NE definition, is shown in Table 3-1 in Chapter 3.

Figure 4-2 shows 2006–2009 investment by area, and Figure 4-3 shows the distribution of 2006–2009 outlays by area, excluding applied research

TABLE 4-1 Technical Areas Within the NNR-NE, 2001 and 2010

2001 Memorandum	Evolution	2010 ONR Project Tabulations
Ship design tools		Ship design tools
Ship structural materials	Broadened[a]	Structural systems
Hydromechanics Advanced hull designs	Merged[b]	Hydromechanics and hull design
Ship propulsion	Narrowed[c]	Propulsors
Ship automation Systems integration	Merged[d]	Automation, control, and system integration
	New[e]	Platform power and energy

[a] "Ship structural materials" has been broadened to "structural systems," reflecting that, in addition to the materials used, structures are the product of their design and the ways in which the materials are used, fastened, and arranged.

[b] "Hydromechanics" and "advanced hull designs," which were listed as separate areas in 2001, have been combined into "hydromechanics and hull design," reflecting the close relationship of the two areas.

[c] A narrowing of focus has occurred. Problems in the "propulsors" field are a subset of the "ship propulsion" area of the 2001 memorandum.

[d] "Ship automation" and "systems integration" have evolved into the "automation, control, and system integration" area.

[e] "Platform power and energy" is now treated as an S&T area, reflecting the importance of integrated electric drive for future combatants using directed energy weapons and to a certain degree addressing some of the technologies included in the 2001 category of "propulsion" and not included in the 2010 category of "propulsors."

SOURCES: ONR 2001; presentation by J. Pazik to the committee, April 6, 2010.

in power and energy. These amounts exclude funding for certain categories of projects that are managed within the Ship Systems and Engineering Research Division but are not considered part of the NNR-NE: projects that are not basic and applied research [that is, grants for Budget Activity (BA) 3 and advanced technology development] and projects dealing primarily with signatures (including basic and applied research). Some research funded by ONR and contributing to the goals of the NNR-NE may be managed in divisions other than ONR 331, including ocean engineering research in ONR Division 321 and research under the Naval Materials Division (Division 332).

The data provided to the committee support the following observations:

- In the 2006–2009 period, funding was fairly stable, with no clear trend in any category.

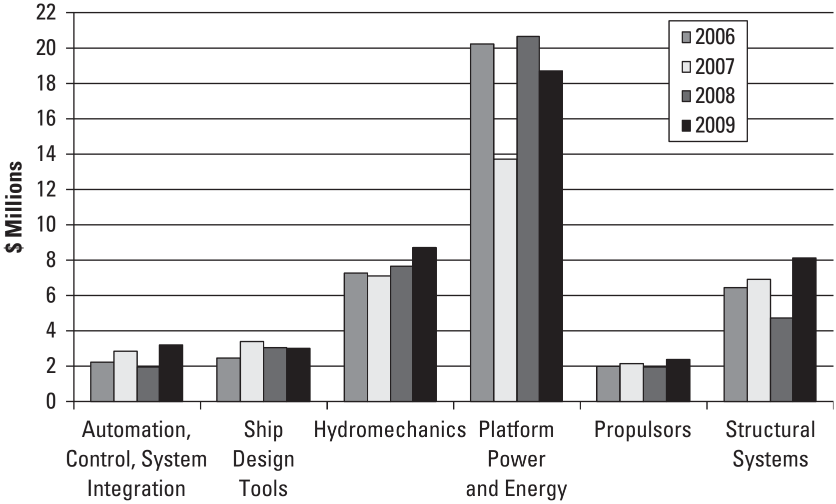

FIGURE 4-2 Outlays for naval engineering basic and applied research grants and contracts by field, 2006–2009.

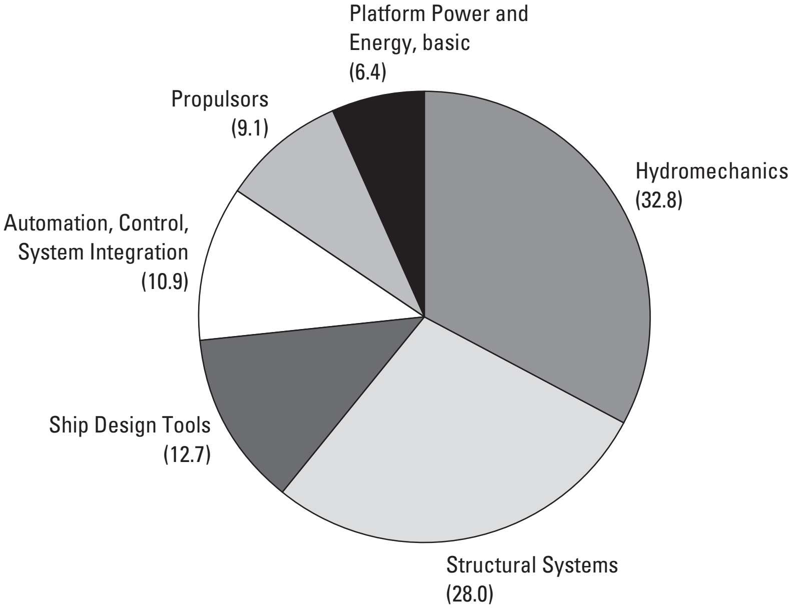

FIGURE 4-3 Outlays for naval engineering basic and applied research by field as percentage of 2006–2009 total, excluding applied power and energy.

- Applied projects in platform power and energy dominated funding during 2006–2009, though this important research field was not mentioned in the 2001 memo. This category accounted for 46 percent of 2006–2009 expenditures, and the average applied power and energy grant was much greater than in the other fields ($1.6 million per year per project versus $126,000 for all other categories).
- When applied power and energy is excluded, the major categories of spending are hydrodynamics and structures.
- Annual grants are relatively small (excluding applied power and energy), although many projects continue for more than 1 year. A strategy of awarding numerous small grants appears to be followed. For example, in hydrodynamics, 80 awards per year of about $100,000 each are made.

The task statement requires that "the study will assess whether these seven disciplines adequately define the scope of NNR-NE." The committee's conclusions concerning the definition of the seven areas (now merged into six) are as follows:

- Advances in all of the areas could be considered as innovations in naval ship design.
- The committee does not see evidence that any of the six fields is "mature" in the sense that the field is unlikely to produce advances that would contribute to ship design and performance.
- Each of the fields, when broadly defined, receives support from sources other than the Navy and has applications beyond naval engineering, but the need to maintain scientific expertise in problems of unique importance to naval engineering justifies including each of the fields within an NNR.
- Power and energy provision will be a critical problem for future naval ships; therefore, this field should remain a part of the NNR-NE.[3] Because of the nature of the research required, this area will continue to require disproportionate funding.
- The major gap in the present definition is inadequate acknowledgment of the need for basic and early applied research to support the integrative function central to the practice of naval engineering. The present

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[3] It is the committee's understanding that ONR basic and early applied research in power and energy may not be managed in the ONR division that houses most of the NNR-NE fields. The definition of NNR-NE should not be dictated by organizational arrangements within ONR.

> portfolio in automation, control, and system integration does not appear to fulfill this need.
>
> **Recommendation:** ONR should retain the six fields of ship design tools; structural systems; hydromechanics and hull design; propulsors; automation, control, and system integration; and platform power and energy in the definition of the areas of basic and applied research within NNR-NE. The definition should state that all ONR basic and early applied research in these fields is to be coordinated to meet the goals of the NNR-NE. In particular, basic and early applied research in platform power and energy should be retained in the definition regardless of where this activity is housed in ONR. In addition, the definition should explicitly identify multidisciplinary systems engineering as an area of basic and early applied research within NNR-NE.

The content of the present system integration portfolio does not address systems engineering as a research discipline. Realizing the ultimate potential value (in terms of contribution to the Navy mission) of a research breakthrough in any one of the six fields in the present NNR-NE definition usually depends on advances in other fields. ONR basic and early applied research should provide an incentive to capitalize on these relationships among the fields, and explicitly defining systems engineering as a research category could help achieve that goal. Without an integrated multidisciplinary systems approach, there are likely to be omissions in basic and early applied research and incorrect projections of the pace and direction of technology development, thereby preventing capabilities from being available when needed.

> **Recommendation:** The Navy should dedicate an important share of its resources for naval engineering S&T to problems that are expected to have broad applicability to a range of possible future ship programs (e.g., research on power systems and on system integration).[4]

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[4] This recommendation is consistent with the ONR Discovery and Invention Portfolio's objective of providing the Navy with technology options (ONR 2009, 26) and with the long-term perspective that the NNRs are intended to take. It also is consistent with the recommendation of the 2005 National Research Council Committee on DOD Basic Research that DOD should define basic research not as research that is designed with no specific application in mind but rather as research that has the potential for broad rather than specific application (NRC 2005, 1).

The committee reviewed the topics of ONR-funded projects in 2006–2009 in each of the NNR-NE fields (ship design tools; structural systems; hydromechanics and hull design; propulsors; automation, control, and system integration; and platform power and energy), received presentations from ONR program officers on objectives and accomplishments in each field, and received presentations from ONR-sponsored researchers. The committee did not review the content or quality of the products from individual research projects. The committee considered the portfolio of projects within each area from the point of view of intellectual quality, mission alignment, and management commitment and resource adequacy.

On the basis of this review, the committee concluded the following:

> **Conclusion:** The research portfolios in some of the fields (including power and energy and structural systems) appear to have strong intellectual quality, are organized around well-defined objectives, demonstrate progress, are aligned with mission needs and potential applications, and are adequately supported.

For certain other fields (including automation, control, and system integration and ship design tools), the intellectual quality and the objectives are not evident, and the project portfolios appear to lack cohesion or to be too narrowly focused.[5,6]

The pattern of funding large numbers of small research projects evident in the portfolios of several NNR-NE fields suggests that the programs in these fields may not be well coordinated toward achievement of a small number of sharply defined goals. A tendency to spread available resources thinly but widely would run counter to the intent of the NNR initiative to ensure that limited resources are sufficiently concentrated to produce results in the most critical fields (Gaffney et al. 1999, 15).

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[5] The underlying source of problems in the less strong portfolios may be traceable to the extent and quality of input from users and the research community in the articulation of research needs and in user evaluations of the research products.

[6] In some fields, relevant research is outside the administrative definition of the NNR-NE. Therefore, the committee did not receive information on these areas, which may address apparent gaps in the NNR-NE portfolio.

Conducting Major Field Experiments

The 2001 memorandum specifies that as part of the NNR-NE, ONR is to "conduct major field experiments that integrate various technologies into innovative ship concepts" (ONR 2001, 3). With the possible exceptions of some applied projects in the power and energy category, none of the research projects sponsored by NNR-NE described to the committee appear to correspond to such a major field experiment. Applied power and energy projects, funded at an average of $1.6 million per project per year, are of sufficient scale to match the concept of a major field experiment that the 2001 memorandum calls for.

Investing in the Development of New Researchers and in the Research Infrastructure

The 2001 memorandum creating the NNR-NE requires ONR to support activities intended to attract and train new researchers and to support the construction and maintenance of physical research facilities. Because the grants and contracts for basic and applied research in the six fields shown in Table 4-1 are expected to produce new scientific knowledge, these funds have some impact on ONR's ability to develop new researchers and the infrastructure needed for that research. In addition, ONR's definition of NNR-NE includes certain activities administered within ONR 331 whose main purpose is educational (i.e., activities to attract students and give them experience, rather than to produce new knowledge). The present study's task statement emphasizes that the scope of NNR-NE education programs is graduate and postgraduate training for researchers; however, the education spending amounts that ONR reported to the committee as elements of the NNR-NE include some undergraduate activities. ONR's outlays for these educational activities in 2006–2009 totaled $5.3 million. The education projects receiving funding in 2009 and their performing institutions are shown in Table 4-2. Among the primary goals of these programs is engaging undergraduates in research or otherwise exposing undergraduates and primary and secondary school students to naval engineering technology, in order to attract students to study and careers in S&T, and especially in naval engineering.

Table 4-3 and Figures 4-4 and 4-5 describe the performing institutions and principal investigators for NNR-NE research projects. The data support the following observations:

TABLE 4-2 Education Projects Receiving Funding in 2009 and Their Performing Institutions

Project	Institution
Naval Systems Undergraduate Research Fellowship Program for the Aerospace Systems Design Laboratory	Georgia Institute of Technology
Atlantic Center for the Innovative Design and Control of Small Ships	Stevens Institute of Technology, with participation of U.S. Naval Academy, Naval Postgraduate School, University College London, Florida Atlantic University, Webb Institute, and industry partners
Marine Applications of Thermoelectric Materials	Maine Maritime Academy
Creation of an Unmanned Surface Vehicle Student Competition	Association for Unmanned Vehicle Systems
Recruiting the Next Generation of Naval Architects	Massachusetts Institute of Technology
Outreach Effort to Attract Young People to Technical and Engineering Careers in the Marine Industry—SeaPerch	Society of Naval Architects and Marine Engineers
Technical Support for SeaPerch Underwater Robotics Student Laboratory Program in Alaska	Naval Undersea Warfare Center
Center for Innovation in Ship Design Innovation Cell Concepts, Design and Analyses Support	NSWC
National Defense Education Program, Preengineering Program Navy Collaborations	U.S. Naval Academy
Center for Reforming Undergraduate Education in Electrical Engineering Energy Systems—A Critical Infrastructure for National Security	University of Minnesota

- Funding is spread among many universities.
- NSWC is a major performer.
- Among principal investigators, the median year of receipt of PhD is 1986.5, implying that the median researcher is in his or her early 50s. It is reasonable for ONR to prefer to support researchers with clear records of performance; however, the small share of grants received by

TABLE 4-3 Institutions Holding ONR Research or Educational Grants or Contracts in the NNR-NE, FY 2009

Institution	Number of Projects
U.S. universities (except federal institutions)	
Arizona State University	1
Brown University	1
California Institute of Technology	5
California State University–Chico	1
Carnegie Mellon University	1
City University of New York	1
Cornell University	4
Duke University	1
Florida Atlantic University	2
Florida State University	3
Georgia Tech	7
Johns Hopkins University	7
Lehigh University	3
Maine Maritime Academy	1
Massachusetts Institute of Technology	4
Mississippi State University	1
Northwestern University	5
Pennsylvania State University	2
Princeton University	3
Rensselaer Polytechnic Institute	3
Stanford University	1
State University of New York–Buffalo	2
Stevens Institute of Technology	1
Temple University	1
Tennessee Tech University	1
University of Akron	1
University of Arizona	1
University of California, Berkeley	2
University. of California, Los Angeles	1
University of California, San Diego	8
University of Delaware	1
University of Florida	1
University of Iowa	4
University of Kentucky	2
University of Maryland	5
University of Massachusetts	2
University of Michigan	10
University of Minnesota	5
University of New Orleans	1
University of Notre Dame	4
University of South Carolina	3
University of Texas	2
University of Utah	1
University of Virginia	1
Villanova University	1
Virginia Polytechnic Institute and State University	7
Western Michigan University	1
Navy and other federal government institutions	
Department of Energy	1
Naval Academy	7
Naval Air Warfare Center	2
Naval Postgraduate School	2
Naval Research Laboratory	5
Naval Surface Warfare Center	46
Naval Undersea Warfare Center	2
Private-sector firms and nonprofit organizations	
ABB Inc.	1
Applied Research Associates, Inc.	1
Association for Unmanned Vehicle Systems	1
BMT Designers and Planners, Inc.	1
Dynaflow, Inc.	4
Force Technology	2
GE Global Research	1
Global Engineering and Materials, Inc.	3
Icosystem Corporation	1
Science Applications International Corporation	5
Society of Naval Architects and Marine Engineers	1
T-Splines, Inc.	1

TABLE 4-3 Institutions Holding ONR Research or Educational Grants or Contracts in the NNR-NE, FY 2009 *(continued)*

Institution	Number of Projects
Foreign research institutions	
Bar Ilan Research and Development Co., Ltd.	1
Bulgarian Ship Hydrodynamics Centre	1
Centre Internacional de Mètodes Numèrics en Enginyeria	1
Cooperative Research Centre for Advanced Composite Structures, Ltd.	3
Imperial College of Science and Technology	1
Istituto Nazionale per Studi ed Esperienze di Architettura Navale	2
Laboratory of Geophysical and Industrial Fluid Flows	1
National Maritime Research Institute	1
Osaka University	2
Seoul National University	2
Stichting Maritiem Research Instituut	2
University of Cambridge	1
University of Newcastle upon Tyne	1

recent PhDs at least raises a question about the effectiveness of NNR-NE in attracting new researchers.

- Principal investigators received their PhDs from diverse academic departments. This suggests that, although naval engineering is a well-defined specialty, naval engineering–related S&T is not a distinct

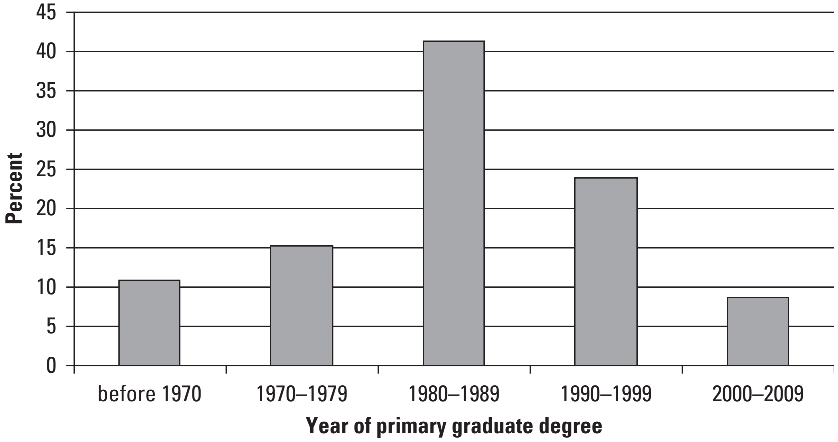

FIGURE 4-4 Distribution of naval engineering 2009 grant holders by year of graduate degree. (Source: Tabulations of ONR 331 basic and applied research projects provided to the committee by ONR.)

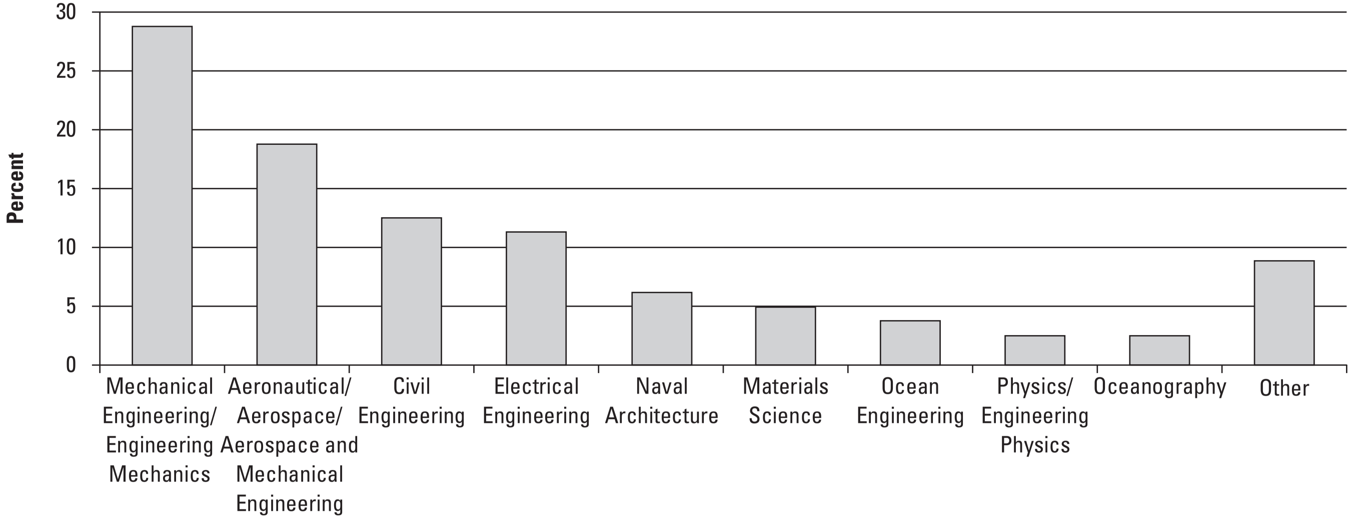

FIGURE 4-5 **Department of graduate degree of naval engineering principal investigators, 2009.** Note: The count for degrees from mechanical engineering departments may include some degrees awarded in ocean engineering programs housed within mechanical engineering departments.

discipline. ONR's challenge is to attract researchers from diverse backgrounds to work on a particular set of problems that are important to the practice of naval engineering.

Planning, Review, and Coordination

The 2001 memorandum specifies that the resources required to fulfill the NNR-NE be sought annually through ONR's Investment Balance Review and that the progress and impact of the NNR-NE be externally reviewed every 5 years. In addition, the 2010 and 2007 ONR instructions (ONR 2010; ONR 2007) defining the criteria for designating new NNRs require that the responsible department report annually on the execution and progress of the NNR and require coordination of the NNR with ONR's Future Naval Capabilities (FNC) technology transition initiatives and with DARPA. The 2001 memorandum also requires ONR to create consortia and partnerships, to award specific numbers of fellowships, and to issue certain broad agency announcements (See Box 1-2). The description of ONR planning and priority-setting for the NNRs provided to the committee (K. Ng, presentation to the committee, May 5, 2010) does not identify these activities explicitly, although some activities may be informally conducted.

Assessment of ONR Naval Engineering Discovery and Invention Activities

The following subsections assess ONR's activities in discovery and invention as contributions to achieving the NNR-NE objectives. Activities in each of six research areas are evaluated as well as the activities addressing education and outreach.

The committee's assessment of the NNR-NE program used the 2010 version of the S&T areas included in NNR-NE and was based on presentations from ONR managers and program officers, presentations and discussions with workshop participants, ONR end-of-year reports summarizing program activities and achievements, papers commissioned by the committee, and presentations from ONR-funded researchers.

ONR identifies the outputs of its S&T investments as knowledge, transitions, and people (ONR 2009, 4). Chapter 3 describes the metrics of these outputs used by ONR; they include publications and patents awarded as a result of ONR-sponsored research, transitions of results of basic and early applied research to use in later-stage applied research and development, and numbers of graduate students and advanced-degree recipients supported by ONR grants. These metrics are indirect measures of the actual benefits of this research to the Navy and the public.

For knowledge, the measures include the number of publications in refereed papers, books, patents, and citations. Assessment based on these measures tends to favor the university component of the naval engineering enterprise, since they are often the end product of the university participants. Each grant explores fundamental concepts, and the output of the work is documented in papers and presentations that are shared with the global community. The traditional peer-review process helps validate the quality of the work, with citations providing a secondary measure of potential quality. In a similar fashion, the non–U.S. Navy government laboratories also can be assessed for their contributions to knowledge on the basis of their publication records. In addition to these outputs, the financial investment in each area is a measure of commitment to each component of the naval engineering enterprise.

The knowledge component provided by industry is difficult to measure in terms of numbers of publications, patents, and citations. Industry is focused on producing real-world designs and hardware. Industries involved in the naval engineering enterprise typically do not pursue patents on their work because of the restricted nature of the majority of designs, thereby limiting the value of this measure. There are, however, a number of commercial research and development firms that do focus on the knowledge component, and their output can be measured by using their publication records.

For transitions, reliable measures include the number of ONR-funded basic research (BA 1) project results directly leading to applied research (BA 2) projects and the number of transitions to ONR's Innovative Naval Prototype (INP) and FNC programs.[7] A database of ONR projects

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[7] The FNC program has been designed to facilitate technology transition to the U.S. Navy fleet. A fundamental component of the FNC program is to establish fleet ownership of the process by creating teams of operating Navy, acquisition, and technical personnel that jointly direct activities addressing capability needs. FNCs consume approximately one-third of the U.S. Navy S&T budget, with $500 million annually distributed to more than 200 individual projects (http://www.navy.mil/navydata/transformation/trans-pg92.html). While the FNCs are near operational concepts, the INP program explores technologies that have the potential to introduce a game-changing impact on the way the Navy operates.

that have transitioned to FNCs and INPs would serve as a valuable tool for assessing the transitions and their associated university, laboratory, or industry sources. ONR management reported to the committee that counts of transitions are used to evaluate the NNRs, but data on NNR-NE transitions were not provided to the committee.

The people component of ONR's S&T output can be measured by numbers of researchers participating, participants in STEM programs, advanced degrees completed by graduate students working on ONR-sponsored projects, and new researchers who received ONR support as students and who join the naval warfare laboratories or who enter the naval engineering industry. Trends of these measures over at least a decade would provide significant samples for assessing and identifying the contributions of each component to the naval engineering enterprise.

NNR-NE Research Portfolio

The committee reviewed the list of ONR-sponsored projects that ONR defines as within the NNR-NE. The committee received briefings from ONR that summarized the content, goals, and accomplishments of research programs in each of the technical areas of the NNR-NE. In addition, ONR-sponsored researchers presented summaries of their work to the committee (see Appendix A).

The committee's observations concerning the research focus, objectives, results, and potential gaps in each of the NNR-NE areas are summarized below. Figures 4-6 and 4-7 show the ONR output metrics for each area: the number of papers and book chapters published and the number of investigators, students, and postdoctoral researchers engaged in NNR-NE projects during 2006–2009. ONR reported these metrics to the committee for each ONR program officer, and the committee assigned them to technical areas according to the primary area of responsibility of each program officer, although some program officers may oversee projects in more than one area. The publication metrics show considerable disparity among technical areas in the rate of paper and book chapter production, even after taking into account differences in research spending among the areas. The committee did not have sufficient information to examine the causes of these disparities. The differences suggest that using the metrics to compare productivity among technical areas would be problematic.

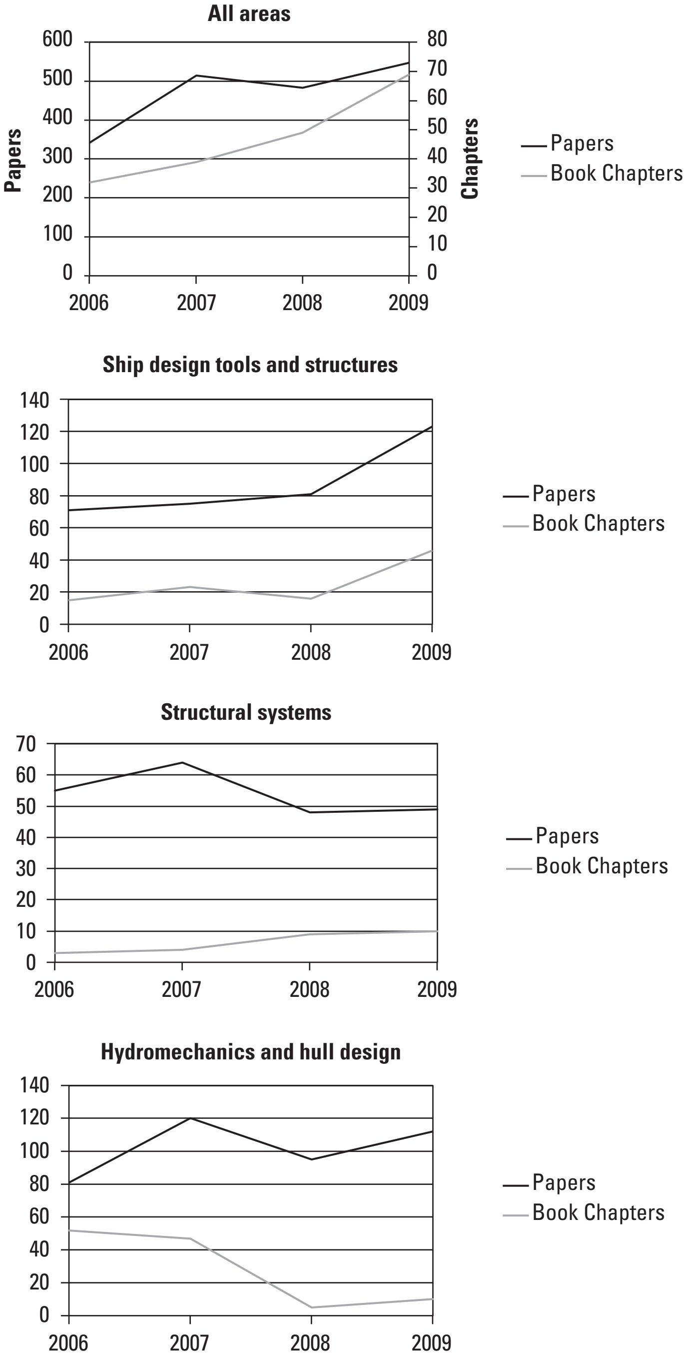
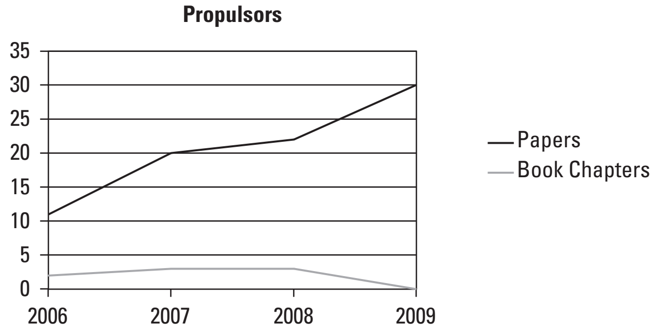
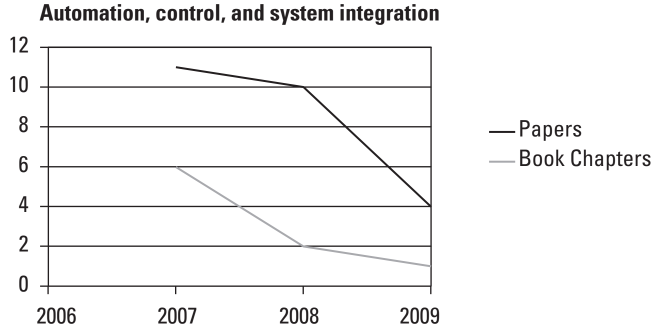


FIGURE 4-6 Journal papers and book chapters published on ONR-sponsored research in naval engineering–related topics, 2006–2009.





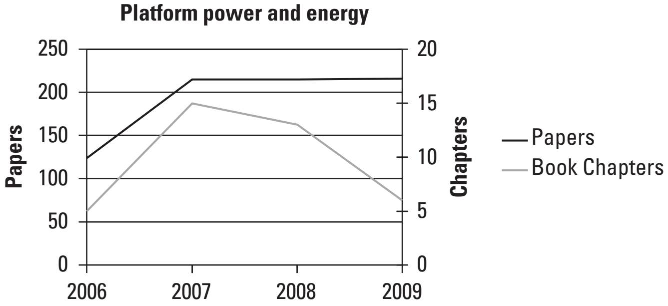
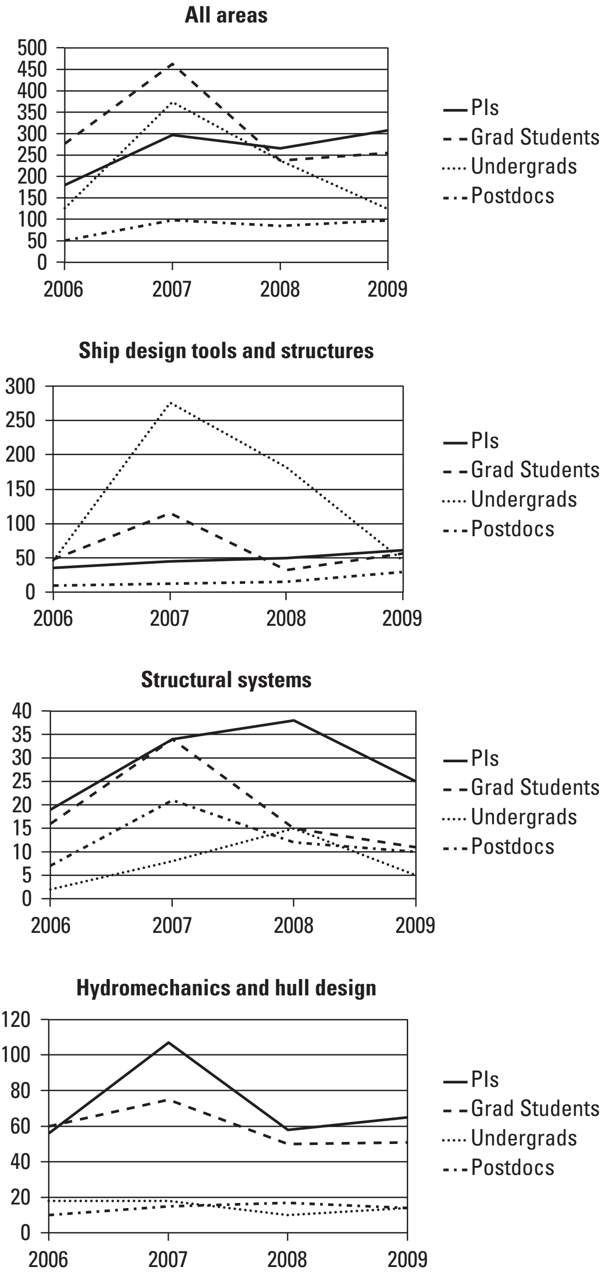


FIGURE 4-6 *(continued)* **Journal papers and book chapters published on ONR-sponsored research in naval engineering–related topics, 2006–2009.**


All areas

Ship design tools and structures

Structural systems

Hydromechanics and hull design

FIGURE 4-7 Principal investigators, graduate students, and postdoctoral fellows supported by ONR-sponsored research in naval engineering–related topics, 2006–2009.

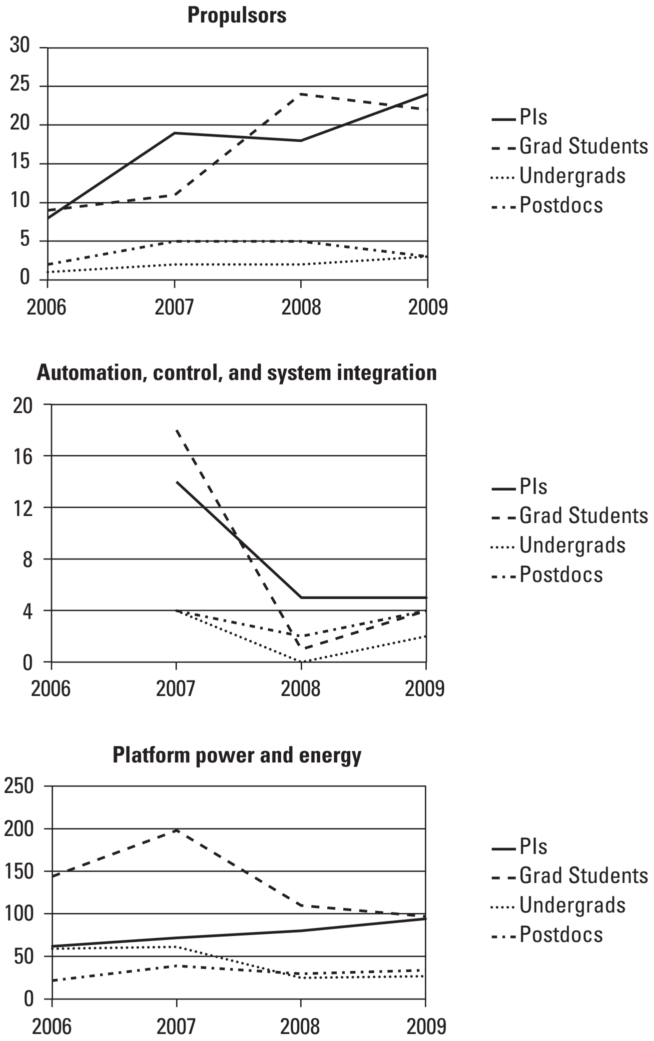


FIGURE 4-7 *(continued)* **Principal investigators, graduate students, and postdoctoral fellows supported by ONR-sponsored research in naval engineering–related topics, 2006–2009.**

Ship Design Tools The research associated with ship design tools within ONR is more diffuse than in other S&T areas. This is, to some degree, the result of the broad nature of ship design and the ultimate integration of research in hydrodynamics, structures, and propulsion into research within the ship design domain.

Structures, hydrodynamics, and propulsion are integral to the nature of ship design. However, much of the research conducted in these areas is in understanding and predicting physical phenomena or, in the case of propulsion research, is devoted to improvement of machinery elements. Tools developed in the hydrodynamics, structures, and propulsion fields are intended to serve needs within those areas, and while they may ultimately be incorporated into tools that could be used by designers at the ship level, this does not appear to happen routinely.

In the course of its information gathering, the committee heard expressions of concern from members of the community that ONR's basic and early applied research is not efficiently leading to development of new or improved practical ship design tools. These concerns appear to vary by technical area, where different standards are used by ONR project officers as to what design tool–related research can be appropriately supported by S&T funding. This was a particular concern in the hydrodynamics area, where the transition to design tools significantly lagged the other areas. There may be a need for closer collaboration between ONR's NNR-NE personnel and technical staffs at NSWC-CD and NAVSEA concerning how design tools that originate from an NNR-NE S&T area should be incorporated in design tools whose purpose is total ship design.

In ONR's presentations to the committee, the objectives and approaches in ship design tools research within NNR-NE were outlined as follows:

The objectives are to

1. Reduce platform design cycle time,
2. Reduce acquisition cost through integrated design and software tools, and
3. Extend design options as long as possible.

The approaches are to

1. Use set-based design models,
2. Integrate emerging research into physics-based technology performance evaluation tools,

3. Complement concept development with analytical tool development,
4. Investigate translation of higher-order physics-based models to faster-running surrogate models appropriate to the order of the needed design fidelity,
5. Treat all aspects of design as variables, and
6. Investigate alternative geometric design representations for alternative analytical techniques.

The committee made use of the 5th Ship Design Process Workshop at the Center for Innovation in Ship Design (CISD) to evaluate ONR's use of these approaches. The workshops are jointly supported by ONR, NAVSEA, and the DOD CREATE program. Research discussed at the workshop was performed by university researchers funded by ONR, by employees of CISD (which is staffed by NAVSEA), and by private companies funded by ONR. This workshop demonstrated that direction of the ONR ship design tools portfolio is integrated with potential end users of the work.

Approach 1, aimed at the development of set-based approaches to the design of complex entities such as ships, is the subject of work being performed with ONR funding. Status reports and discussions of ONR-supported projects addressing Approaches 3, 4, and 5 were also part of the workshop. Work is being done to improve the modeling of the design process itself; a new approach to improving the effectiveness of early-stage design, called continuous collaborative concept formulation, is being explored by a number of participants, including ONR researchers.

While ONR's stated approaches were developed specifically to support Objectives 1 through 3, some of the objectives are being addressed directly by ONR-funded work. Reducing ship costs by reducing design cycle time is a central objective of the collaboratively performed project of modeling the design process. This program includes tool capability analysis, staff capability analysis, and planning tools to support acquisition program managers and ship design managers.

The ONR-funded design research at universities is closely aligned with work being done by NAVSEA personnel, who both apply the research and assist the ONR project managers in connecting the research objectives to Navy needs. The BA 1 and BA 2 ship design tools research projects sponsored by ONR and other programs generally are coupled closely with subsequent BA 3 research activities, although those investments have been limited by funding availability. In addition, the performers in this research domain usually are well known to each other and have opportunities to communicate through workshops supported by ONR, NAVSEA, and DOD CREATE. Even though university research is funded by ONR and later-stage work is performed by government employees supported by NAVSEA and DOD CREATE, the existence of CISD helps ensure that these various entities are well connected to each other.

Structural Systems Structural systems basic and early applied research at ONR appears to receive significant attention. The research areas generally have clear potential value to naval engineering. The evident objectives of the NNR-NE structures portfolio include the following:

- Developing technologies for life-cycle performance analysis and monitoring of ship structural systems;
- Understanding the behavior of novel ship structures, such as composite and aluminum subsystems, during and after fire to enable modeling and predictions;
- Providing a protection system or armor that can defeat several threats and meet structural and stiffness requirements; and
- Facilitating use of alternative hull forms that are lighter, more survivable, stealthier, cheaper, easier to maintain, and longer-lived than steel or aluminum hulls.

Structural systems research places strong emphasis on structural survivability after fire and explosions and on materials other than steel, such as composite and aluminum structures. In research areas within the portfolio such as fire resistance of composites, blast-resistant polyurea coatings, and fully coupled fluid–structure interaction simulations, there are breakthrough opportunities. The work on isogeometric analysis could lead to a breakthrough in structural and fluid–structure interaction analysis.

In the structural systems portfolio, basic research topics are awarded to academic institutions, and applied research topics are awarded to applied research laboratories such as NSWC-CD, the Naval Research Laboratory, and industry research organizations. The ratio of basic to applied structural systems projects is approximately 2:1; however, ONR's FNC program also conducts applied structures research. Although budgets are limited, there appears to a balance between new and continuing projects.

Certain structures topics important for naval engineering are not in the portfolio, including coatings and fatigue life extension. These are topics of basic and early applied research in other ONR divisions not included within the NNR-NE definition. Other topics that are relevant to naval engineering but administered outside the division responsible for NNR-NE include bearings and lubrication.

Navy plans call for building fewer new classes of ships and sustaining the fleet through production of ships according to modified versions of existing designs. Existing ships will continue in service longer and be subject to modernizations to extend service life. These decisions have implications for the relative importance of research on structures, design tools, and other technical areas within NNR-NE. The committee could not identify research programs in the NNR-NE portfolio that addressed this future need.

During the committee workshops, a number of concerns were expressed by members of the community who identified areas that they believed should receive additional attention, including the following:

- Development of more efficient structural concepts using high-strength, lightweight materials that are very durable;
- Development of computer simulation tools. Research is needed on solving problems associated with multiscale and multiphysics modeling, real-time integration of simulation methods, model validation and verification, and the handling of large amounts of data; and
- Improved computational efficiency and accuracy of solvers by incorporating adaptive multiscale techniques and tight multiphysics coupling techniques in combination with the use of massively parallel processors.

Hydromechanics and Hull Design; Propulsors The two principal themes in the portfolio of recent ONR basic and early applied research in hydromechanics and propulsors are (*a*) simulation-based analysis and design capabilities to augment or replace traditional physical test–based approaches and (*b*) targeted research to address high-priority areas in nonacoustic detection, extreme motions, and loads.

A major share of ship-related research concerns large-scale computational fluid dynamics. The portfolio includes a significant commitment to the conduct of prototype tests by complementary efforts at NSWC-CD. The commitment to testing appears healthy and indicates that ONR recognizes that progress requires a balance between experimental and computational work. Propulsor modeling has a much higher profile than a decade ago, with emphasis on crash-back maneuvers. Investigators are taking diverse approaches to this problem.

The objectives of several recent projects are prediction and control of bubbly wake and the understanding of turbulent flow in the vicinity of contact lines. The need for ever-greater detail in hydrodynamic modeling is a concern. As computing capability has increased over the years, software tools have been developed to provide discrimination at smaller and smaller scales. It is unclear whether this focus is a valid research direction for prediction of forces, acoustic sources, and other elements of practical relevance at appropriate scales of interest.

Current ONR-sponsored propulsor research focuses on unsteady cavitation, highly separated flows, hydroacoustics, and advanced propulsor concepts. In addition, as waterjets become more widely used for high-speed vessels, research in cavitation of waterjets is growing.

Workshop participants cited the need for improved integration of propulsor and hull hydrodynamic interaction on naval ships and the subsequent integration of such research to develop useful design tools. Other areas noted as in need of greater emphasis include

- Predictive tools for propulsor performance in extreme ship motions,
- Development of interactive educational tools in propulsor design,
- The understanding of unsteady forcing and development of analysis tools required to design vessels with unsteady flow control,
- Improved methods for understanding the effects of turbulence on fluid motion, and
- Production of computational fluid dynamics results in near real time.

Automation, Control, and System Integration The portfolio in automation, control, and system integration should be growing and dynamic because the increasing complexity of ships is a key technical problem confronting naval engineering. However, the focus and overall objectives of the automation, control, and system integration portion of the portfolio were not evident to the committee. The portfolio includes some highly applied projects, but basic research of broad potential applicability on system integration, system engineering, and system architecture appears to be absent from the NNR-NE.

Recent projects in this research area concern the control of heterogeneous systems, adaptive automation for machinery control using a total ship approach, and increased cognitive functions of automated systems. Automated testing and design of damage-resilient ship subsystems are also being pursued. These topics are related to the Navy's desire in recent years to reduce shipboard manning because of its long-term costs; however, the long-term effect on ship readiness of such reduced manning is of growing concern.

While progress in these areas holds the promise of transforming ship and vehicle design, the likelihood that such capabilities will bring with them increased vulnerability to system failures and increased (and unpredicted) severity of such failures cannot be ignored. Taking full advantage of automation and its integration in system control while avoiding the pitfalls of reduced manning during the evolution of an emergency remains a challenge.

It is apparent that automated and "smart" systems capabilities will be of growing importance with the emergence of all-electric ships, integrated electric propulsion, and the desire for operations that are both robust and robustly reconfigurable. The increased use of autonomous unmanned vehicles and the increased availability of smart sensors make total ship adaptive automated control of heterogeneous systems an alluring goal.

Shipboard damage control would likely benefit from research in this area. Historically, this capability has been heavily dependent on significant manpower resources, and many activities required to control or ameliorate damage are heavily dependent on personnel. However, aspects that could benefit from smart automated and adaptive systems remain: the ability to configure shipboard systems rapidly to survive anticipated hits, systems that detect and evaluate damage and fire spread and provide guidance to crews, and control of deflooding systems.

Platform Power and Energy This research area was not listed in the 2001 ONR memorandum creating the NNR-NE, yet in 2006 through 2009 (the years for which research spending data were provided to the committee) it was the largest component of the NNR-NE portfolio, with the most funding for applied research projects. The research was aimed at supporting development of components and systems for providing shipboard power of very high capacity compared with historical requirements. As noted in Chapter 3, the Navy's 2011 research and development budget estimate reports a decline in 2010 in all Navy applied research (BA 2) spending for power and energy. Applied research funding for the budget category "surface ship and submarine hull mechanical and electrical (HM&E)" declined from $79 million in FY 2009 to $46 million in FY 2010 (DON 2010, 135). The budget estimate document states that the decrease is due to the completion of an energy and power technology initiative, apparently a reference to a DOD-wide 5-year program begun in 2002 to coordinate research and development on energy efficiency technology improvements (Taylor et al. 2010).

The use of power electronics–based integrated power systems (IPS) to manage power and energy needs and efficiency could have great impact on the performance of future Navy ships. ONR has correctly defined and pursued a research and development plan for such a system. However, gaps in Navy planning threaten the transition of this technology from ONR research and development to application.

The definition of power electronics–based IPS and the design of its components, including converters, generators, energy storage systems, and design tools for more conventional ship designs and weapon system power loads, are adequately emphasized. However, there is inadequate research and development on the dynamics of future systems, where weapon load requirements may far exceed the capacity of available generation and therefore large energy storage systems will be essential. The integration of power electronics–based IPS into the overall ship design is also not adequately emphasized. Attention to this problem is essential if future ships are to accommodate radar and weapon systems that the Navy may wish to use.

Education Initiatives

ONR's support of university research makes an essential contribution to sustaining the supply of researchers available to work on basic and applied naval engineering research problems. Beyond this function, ONR's present conception of the NNR-NE lacks a clear definition of the scope of the educational activities that are to be considered a part of the initiative. Some provisions of the 2001 memorandum and some descriptions of the NNR-NE initiative that ONR presented to the committee indicate that the scope of NNR-NE may include a broader range of educational aims, including STEM education and promotion of training of professional naval engineers.

ONR has been assigned primary responsibility for the Navy's contribution to the nationwide STEM initiative. This activity is managed at the corporate level as a single program rather than as separate programs within the divisions. ONR is a suitable home for the activity because its staff understand the importance of the initiative and the elements of scientific literacy. However, the practical significance of managing STEM as an element of the NNRs is not evident.

Ensuring an adequate naval engineering professional workforce is a primary concern of NAVSEA, because that command, directly and through its contractors, employs most engineers in the field. However, ONR research grants in naval engineering have an important indirect role in providing the professional workforce. Faculty research funding is essential to the survival of naval engineering professional programs because research ensures the intellectual vibrancy of university academic programs. ONR research investments should be directed according to the value to the Navy of the scientific knowledge they produce, but the connection between research support and professional workforce supply cannot be overlooked.

Contribution of ONR's NNR-NE: Summary Observations

The committee's assessment of the NNR-NE began by comparing ONR's activities since 2001 with the specified actions that would be taken to fulfill the NNR-NE. The purpose and constituent activities of the NNR-NE according to the 2001 memorandum are summarized in Box 1-2 in Chapter 1.

The 2010 and 2007 ONR instructions stating the policy for designating an S&T initiative as an NNR specify activities required in NNR initiatives (ONR 2010, 3–4). The department responsible for an NNR is to

- Formulate thrust areas within the field to provide S&T products sufficient to ensure naval superiority,

- Coordinate the NNR with other efforts including ONR FNC technology transition initiatives and activities at DARPA,
- Augment basic research with experiments focused on promoting applications and balance theoretical with experimental research,
- Promote knowledge base development and retention through a military officer fellowship program or an entry-level faculty support program,
- Report annually on progress of the NNR, and
- Submit the NNR to review by an independent board at least every 5 years.

The requirements in the 2010 instruction that are not found in the 2001 memorandum are annual reporting and coordination with FNC and non–Department of the Navy activities.

The conclusions below address the degree to which ONR has carried out the required activities. The committee concluded that there are substantial opportunities to improve ONR's execution of the NNR-NE mission. The specific conclusions are as follows:

- NNR-NE meets a Navy need but requires planning and stronger links to users and researchers.
- NNR-NE has not yet gained recognition within or outside ONR as the focus of naval engineering basic and early applied research.
- ONR does not appear to have conducted the reporting called for in the 2001 memorandum establishing the NNR-NE.
- The role of NNR-NE in the Naval S&T Strategic Plan has not been clearly defined.
- ONR has not defined the practical significance of NNR designation for administration and budgeting.
- Some activities called for in the 2001 memorandum or the 2010 instruction have not been undertaken.
- The scope of NNR-NE functions and responsibilities with respect to education and relevant research outside the Ship Systems and Engineering Research Division lacks clear definition.

Conclusion: NNR-NE meets a Navy need but requires planning and stronger links to users and researchers.

The committee concluded that research and educational activities within NNR-NE have fulfilled certain of the Navy's needs to sustain S&T in naval engineering–related fields. Specifically, a diverse research program is supported, and significant numbers of graduate and postdoctoral students are involved (see Figure 4-7). An outreach program is making efforts to attract students into the field of naval engineering at the kindergarten through 12th grade, undergraduate, and graduate levels. Finally, the physical infrastructure of laboratories and equipment, which receives important support through ONR research grants, appears to be adequate for current needs.

However, the NNR-NE initiative has yet to reach its potential. In particular, the vision in the 2001 NNR-NE memorandum of systematic and coordinated management of a research portfolio toward attainment of clearly defined objectives has not been fulfilled. ONR has continued to support important basic and applied research in the designated technical fields, as it did before 2001, but the NNR-NE initiative has not had visibility internally or externally, and the coordination and evaluation steps called for in the memorandum have not been conducted consistently. Reinvigorating the initiative by returning more closely to the letter and spirit of the 2001 memorandum would enable ONR to achieve the purposes of the initiative more reliably and efficiently. Effectiveness would be increased if ONR developed a more rigorous procedure for defining meaningful objectives for research in each of the fields within NNR-NE and measuring progress toward them and if ONR reinforced communications channels between NNR-NE managers and the broad user and research communities.

> **Conclusion:** NNR-NE has not yet gained recognition within or outside ONR as the focus of naval engineering research.

ONR created NNR-NE as a mechanism to focus its basic and applied research and education activities in support of naval engineering and to emphasize the importance of technical progress in naval engineering to Navy missions. However, NNR-NE has never attained the intended status or visibility. Marketing—outreach to the research community to help attract the best talent and ideas and outreach to sponsors and other stakeholders to ensure that the initiative remains relevant to their needs and maintains their support—is a necessary adjunct to the NNR-NE initiative.

> **Conclusion:** ONR does not appear to have conducted the reporting required by the 2001 memorandum establishing NNR-NE.

The management of a collection of ONR activities in a coordinated manner to reach a common objective is essential to the NNR concept. The 2010 NNR instruction requires that the responsible department report annually on the execution and progress of the NNR. Regular progress reporting is a necessary step toward ensuring that the elements of NNR-NE are managed as a unified initiative and recognized by ONR managers, researchers, and clients as the focal point of naval engineering–related basic and early applied research. The 2001 memorandum establishing the NNR-NE specifies that the progress and impact of the NNR-NE be subjected to an external review every 5 years. The committee did not receive documentation of past progress reports or evaluations of the NNR-NE.

> **Conclusion:** The role of NNR-NE in the *Naval S&T Strategic Plan* is not clear.

ONR's 2009 *Naval S&T Strategic Plan* refers only briefly and generally to the NNRs. The plan states objectives for naval engineering research in such broad terms (e.g., platform survivability, stealth, efficient energy and power systems, "new and novel advanced platform design," reduced total ownership cost of naval platforms) that the document appears to be of limited use to research managers in setting priorities and balancing their programs. Correspondingly, ONR has not taken the initiative to relate its NNR-NE portfolio to the *Naval S&T Strategic Plan* and to communicate the importance of efforts carried out under the NNR to the strategy. This is an essential step in ensuring internal understanding of the critical nature of the NNR-NE and of the merits of providing the NNR-NE initiative with adequate resources.

> **Conclusion:** ONR has not defined the practical administrative significance of NNR designation.

The ONR 2001 memorandum establishing the NNR-NE and the 2010 instruction defining the NNRs do not identify the practical consequences of NNR designation, that is, how designation of a portfolio of ONR activities as an NNR alters the management or objectives of the activities. ONR was already engaged in all or nearly all of the activities that the 2001 memorandum designated as elements of the NNR-NE before the memorandum was issued. The committee's understanding is that, rather than initiating new programs, the memorandum served as a declaration of policy: assigning the NNR designation indicated that (*a*) the listed activities deserve special priority in planning and budgeting at ONR because the identified S&T fields are critical to the Navy and no one else will support them and (*b*) management of these activities must be coordinated with the declared policy objective in mind. However, the significance of NNR designation is not explicit in the ONR memorandum or instruction.

Specific actions that ONR could incorporate in the NNR-NE initiative to promote and strengthen naval engineering–related research could include periodic evaluations of research output, periodic examinations of the health of the field and of the performance of all Navy programs supporting the field, procedures for giving priority to the NNR-NE fields in ONR program planning and budgeting, and management arrangements to ensure coordination of all relevant ONR activities toward achieving the shared NNR-NE objectives.

> **Conclusion:** Some prescribed NNR-NE activities may not have been undertaken.

A number of activities specified in the defining NNR documents have not been completed. The 2010 NNR instruction requires coordination of the NNRs with ONR's FNC technology transition initiatives and with DARPA. The 2001 NNR-NE memorandum requires ONR to create university–industry–laboratory consortia for fostering naval engineering S&T. The committee was not presented with information on how these requirements have been interpreted and carried out. ONR does not appear to have conducted large-scale field experiments within the NNR-NE research project portfolio, with the possible exception of certain power and energy applied research projects, or to have issued special broad agency announcements to fulfill specific objectives of the NNR-NE, as the 2001 memorandum calls for.

> **Conclusion:** The scope of NNR-NE functions and responsibilities lacks clear definition.

The 2001 NNR-NE memorandum and the 2010 NNR instruction are imprecise as to how naval engineering–related basic and applied research conducted by units other than the ONR Ship Systems and Engineering Research Division should be coordinated with NNR-NE and as to the scope of educational activities considered to be within the NNR-NE.

The committee's assessments of the significance of NNR-NE research were complicated by the lack of a full picture of ONR work related to naval engineering. Particularly in the fields of ship design tools; structures; and automation, control, and system integration, the committee understands that some amount of relevant basic and early applied research is being conducted in ONR divisions other than Ship Systems and Engineering Research. Coordination of all relevant ONR research with the objectives of the NNR-NE appears to be missing in the management structure of this initiative.

> **Recommendation:** ONR should administer the NNR-NE program with an organization clearly aligned with that envisioned when the NNR-NE was established. To that end, the following actions should be taken:
>
> - ONR management should ensure that the elements and objectives of the NNR-NE are communicated to researchers, program officers, and research product users. In addition, ONR management should ensure that new activities are within the scope of the NNR-NE and contribute to the initiative's objectives.
> - ONR should develop an enterprisewide information system that would make summary information on NNR-NE research projects readily available to proposers and to ONR's clients. Summary information should include an abstract, funding history, and a point of contact for each project. These summaries would be an effective means of informing prospective proposers of ONR's interests and funding priorities and would help keep ONR's clients in the Navy and shipbuilding informed of ONR research.

- ONR should use the information system as a management tool for assessing NNR-NE progress and funding allocation trends; for performance benchmarking; and for communicating NNR-NE progress, achievements, and potential.
- ONR should prepare an annual report that compares the year's activities with those prescribed in the 2001 memorandum and the 2010 instruction. The annual report would serve as a historical record describing how the NNR designation helped achieve the NNR-NE's objectives and promoted the coordination of ONR naval engineering activities.
- Revisions of the *Naval S&T Strategic Plan* should delineate the expected contributions of the NNR-NE to the plan.
- To fulfill the requirement of the 2001 memorandum for creation of consortia to foster naval engineering S&T, ONR should consider the alternative organizational models for cooperative research proposed by the 2002 National Research Council Committee on Options for Naval Engineering Cooperative Research (TRB 2002).
- ONR should revise the definition of NNR-NE, specifying educational responsibilities and requirements for coordination of naval engineering–related basic and applied research outside the Ship Systems and Engineering Research Division. The definition should specify that all relevant research be coordinated through the NNR-NE, regardless of its location in the ONR organization. Requirements in the 2001 memorandum that have not proved useful should be eliminated.

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Abbreviations

DON	Department of the Navy
NRC	National Research Council
ONR	Office of Naval Research
TRB	Transportation Research Board

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Annex 4-1

NNR-NE Scientific and Technical Areas

Definitions and Rationales

ONR provided the committee with the lists below, which summarize the objective, approach, Navy-unique characteristics, and expected payoff of the ONR research portfolio in each of five of the NNR-NE technical areas—hydromechanics and hull design; structures; propulsors; automation, control, and system integration; and ship design tools—and for the educational grant component of the NNR-NE.[8] ONR did not provide such a list for the platform power and energy technical area.

HYDROMECHANICS AND HULL DESIGN

Objective:

- Identify, understand, predict and control the fundamental phenomena of turbulence, cavitation, breaking waves, bubble generation and hydroacoustics.
- Develop reliable physics-based computational prediction capabilities to limit hydrodynamic surprises for new platforms.

Approach:

- Understand the independent and coupled roles of roughness, various geometry complexities, drag reduction technologies, hydroacoustic sources, separated flows, unsteadiness, etc. on turbulent flows.
- Develop theoretical and computational tools that have sufficient physics to accurately predict performance.

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[8] Presentation by J. Pazik to the committee, April 6, 2010.

- Understand the independent and coupled roles of geometry and fluid properties (e.g., density profiles) on wake physics.
- Study the interaction of platforms in close proximity.
- Explore hydrodynamics of motions (e.g., interaction of flows between hulls), seaway effects (e.g., maneuvering in waves), and shape optimization.
- Develop wave measurement from radar, fast wave prediction, and appropriate ship response.

Navy Unique:

- Potential for radical or violent maneuvers used to defend against attack.
- Requirement to operate in all sea states.
- Replenishment at sea.
- Frequent course changes.
- Operations in deep and shallow waters.
- Stealth.

Payoff:

- Establishment of safe operating envelope for vessels in extreme sea states.
- Physics-based computation methods.
- Knowledge databases for understanding and tool validation.
- Computational tools, including shape optimization.
- Advanced hull form designs and operability.
- Energy-efficient hull forms.

STRUCTURES

Objective:

- Develop technologies for life cycle performance analysis and monitoring of ship structural systems.
- Develop an understanding of behavior of novel ship structures, such as composite or aluminum subsystems, during and after fire to enable modeling and prediction.
- Provide protection system and armor that can defeat several threats and meet structural and stiffness requirements.

- Facilitate use of alternative hull forms that are lighter, more survivable, stealthier, cheaper, easier to maintain and have a longer life than steel or aluminum hulls.

Approach:
- Develop reliability-based, structural performance and degradation models and supporting technologies.
- Develop ship structural health monitoring technologies to provide basis for life-cycle management and operator guidance.
- Develop vulnerability assessment capability for light-weight ship structures based upon an improved understanding of material and structural response and life-cycle degradation effects.
- Develop the ability to model the failure of naval composite structures under air blast and after fire.
- Develop models describing the effect of the implosion of a pressure vessel.

Navy Unique:
- Composites and lightweight structures improve stealth and reduce weight, corrosion, fatigue, and maintenance and operational costs.
- Rules and tools necessary to develop novel systems with tailored response against shock and impact that minimize damage on structures, vehicles, personnel and sensitive equipment is needed.

Payoff:
- Advanced structural health monitoring systems that will sustain the life of naval vessels.
- Tools that will assess the performance of new structural components in naval vessels.
- Comprehensive, integrated toolsets and processes to accurately assess the stability and structural integrity of a damaged ship.
- Understanding of heat conduction, charring, buckling, and residual strength of composites under simultaneous heat and load.
- Predictive tools on long-term availability.

PROPULSORS

Objective:

- Improve propulsive efficiency and optimize propulsor for given Naval application.
- Provide the Navy with quiet, efficient and affordable propulsor concepts and capabilities that will meet emerging mission requirements.

Approach:

- Evaluate novel design such as counter-rotating props for fuel efficiency.
- Exploit novel materials in the design of the propulsor to improve hydrodynamic efficiency and blade performance.
- Develop accurate, reliable and robust predictive–simulation tools and methods for design and behavior of propulsors.
- Explore and demonstrate at lab-scale novel propulsor concepts.

Navy Unique:

- Navy propulsors must be able to survive high intensity impulse loads caused by underwater explosions.
- Navy propulsors must also be efficient, affordable, quiet and easily maintained.
- Integrated with naval platforms.

Payoff:

- Propulsion options for high-speed ships that support critical missions.
- Efficient and robust models to advance fundamental knowledge of rotating marine structures which operate with complex, turbulent flows.
- Advanced waterjet design and analysis technology.
- Understanding of the fundamental aspects of two-phase propulsion.

AUTOMATION, CONTROL, AND SYSTEM INTEGRATION

Objective:

- Develop science and technology necessary to demonstrate distributed monitoring and control of hull and mechanical and electrical

systems for Navy vessels (including electrical, auxiliary, and damage control systems).
- Develop and prototype an autonomous, distributed control system featuring the integration of fluid, thermal, and power systems.

Approach:
- Construct a reduced-scale hardware in-the-loop evaluation platform for agent-based control system testing–warship intelligent control system multi-institution demonstrator.
- Perform hardware in-the-loop test and evaluation.
- Develop medium-scale integration of NAVSEA-Philadelphia fluid and thermal systems with remote Purdue power system test bed.
- Develop and demonstrate an intracompartmental integrated wireless sensing and data network.
- Investigate actuation technologies and approaches.
- Develop rapid damage recoverability decision support for structural system to support the fleet with existing and future ships and vessels.

Navy Unique:
- Navy ships are complex platforms composed of disparate systems where interactions and interdependencies are extensive and nonlinear.
- Overall system behavior cannot be inferred from the analysis of an individual portion.
- The dynamic environment with the potential of severe stresses is unique to naval platforms.
- True automation provides increased platform performance, faster decision time, increased survivability and recoverability, optimal manning, and increased safety.

Payoff:
- Demonstrated distributed monitoring and control architectures.
- Integrated, automated operation and reconfiguration of shipboard machinery systems.
- Optimized manning, survivability, and recoverability.

SHIP DESIGN TOOLS

Objective:

- Reduce platform design cycle time.
- Reduce acquisition cost through integrated design and software tools.
- Extend design options as long as possible.

Approach:

- Set based approaches.
- Integrate emerging research results into physics-based, technology performance evaluation tools.
- Complement concept development activity with analytical tool development and model testing.
- Investigate translation of higher order physics-based models to quicker running surrogate models appropriate to order of design fidelity.
- Determine methodologies to treat all aspects of the design as a variable.
- Investigate alternative geometric design representations for alternative analytical techniques.

Navy Unique:

- Integration of complex war-fighting systems.
- Large variability in operational profile.
- Interfaces with proprietary design software.

Payoff:

- Support for innovative design concepts.
- Provision of traceability in design process applications.
- Intelligent search of design space.
- Provision of methodology to deal with uncertainty and variability of inputs and designs.
- Systems optimization.

EDUCATION AND UNIVERSITY LABORATORY INITIATIVE

Objective:

- Provide capable and knowledgeable future workforce in Naval engineering.
- Maintain and enhance education infrastructure (programs, departments) to ensure education and research programs.

Approach:

- Partner with professional societies to create venues for student interaction with Navy labs, design agents, and focus universities.
- Leverage existing K-12 technology education infrastructure.
- Include real world Navy challenges.
- Leverage existing programs in outreach and education.
- Expand existing local programs.
- Insert outreach efforts into undergraduate level engineering courses.
- Focus ONR efforts on advanced degree capabilities.

Navy Unique:

- U.S. citizens required to work in naval facilities.
- Engineering optimizations in platform design and build different than private sector.
- Undersea naval engineering opportunities very limited in private sector.
- Amphibious capabilities.

Payoff:

- Development of an Experimental Introduction to Marine Engineering.
- Increase in student awareness of Naval Engineering course of study.
- Expansion of Sea Perch Program using Society of Naval Architects and Marine Engineers.
- Expansion of number of teams participating in Autonomous Underwater Vehicle Competition.
- Feedback from schools—enrollment in these programs is increasing, direct links to this effort.

Annex 4-2

Earlier Assessments of the State of Naval Engineering

The 2001 ONR memorandum that created the NNR-NE cited the conclusions of a number of assessments of the status of naval engineering in the United States as evidence of the need for the Navy to take a leading role in investment in science and technology in the field (National Naval Program for Naval Engineering, Oct. 22, p. 1). Below are summaries of the following studies cited in the memorandum:

- National Research Council. 1996. *Shipbuilding Technology and Education.* National Academy Press, Washington, D.C.
- American Society of Naval Engineers. 1998. Preserving Our Naval Engineering Capability. *Naval Engineers Journal,* May.
- Chryssostomidis, C., M. Bernitsas, and D. Burke, Jr. 2000. *Naval Engineering: A National Naval Obligation.* Massachusetts Institute of Technology Ocean Engineering Design Laboratory, May.
- National Research Council. 2000. *An Assessment of Naval Hydromechanics Science and Technology.* National Academy Press, Washington, D.C.
- U.S. Department of Commerce. 2001. *National Security Assessment of the U.S. Shipbuilding and Repair Industry.* May.
- Transportation Research Board. 2002. *Special Report 266: Naval Engineering: Alternative Approaches for Organizing Cooperative Research.* National Academies, Washington, D.C.

National Research Council, *Shipbuilding Technology and Education,* 1996

The following were among the findings of this study:

- ONR should continue to support faculty members through fellowships, through research projects directed at Navy objectives, and, to the extent possible, through projects that have economic impacts.

- Naval architecture and marine engineering schools should become more involved with the U.S. shipbuilding industry through research in business-process, system, and ship-production technologies, as well as by soliciting support for these and other kinds of research. The schools should continue concentrating on subjects traditionally taught but should also pay much greater attention to the economic health of the industry. Universities, with their multiple disciplines, led by the naval architects and marine engineers who justifiably lay claim to being good systems thinkers, should be able to seize the problem that U.S. shipbuilders face; understand what it will take to create a healthy industry; and reach as far afield as needed to understand the cultures, political motivations, and economic infrastructures of international competitors.

The focus of this study was naval architecture and marine engineering, and early activity related to the NNR-NE tended to have this perspective. Naval engineering as it is now understood embraces many more academic and professional disciplines, though naval architecture and marine engineering are largely seen as key contributors to total ship engineering. Appreciation of this total ship approach has increased in recent years.

American Society of Naval Engineers, “Preserving Our Naval Engineering Capability,” 1998

The American Society of Naval Engineers undertook the development of a white paper specifically addressing the need to maintain a robust naval engineering capability, in all its facets, in the United States. In this paper, the reader can see the developing line of thinking that led to ONR’s establishment of the NNR-NE. The paper contains the following discussion and recommendations:

- The problem [of maintaining a robust naval engineering capability] is not just a shipyard or ship design issue. It involves the full spectrum of naval engineering including

  - The research, development and operational evaluation of command control, weapon systems, ordnance, aircraft and ship mechanical and electrical machinery;
  - The engineering and integration of the individual command control, weapon and machinery systems into effective combat, electrical and propulsion systems;
  - The physical and functional integration of these systems into combatant ship designs.

- Unless there is a national commitment to a design and construction program in the years ahead, we cannot expect to attract engineering students into the profession, . . . universities . . . will be forced to eliminate their naval engineering curricula. There must be challenging and interesting career opportunities. . . . This reinforces the necessity for the U.S. to commit to sustain at least a minimum level of naval engineering, design and construction activity.
- Commitment to a scaled down but aggressive weapons and ship systems R&D program coupled with the periodic construction of at least a few complex warships of new design is essential if the U.S. is to retain naval technological and warfighting supremacy.

Recommendations:

- [The Navy should make a commitment to] . . . a planned, budgeted program for periodic ship design and construction.
- [The Navy and others should make a long-term commitment to] . . . sustain naval engineering education.
- [The Navy needs to] . . . produce a plan.

C. Chryssostomidis, M. Bernitsas, and D. Burke, Jr., *Naval Engineering: A National Naval Obligation,* 2000

This study also focused significantly on naval architecture and marine engineering. An excerpt from this paper follows:

> As part of its national obligations, ONR must ensure U.S. world leadership in those unique technology areas that insure naval superiority. ONR accomplishes this mission through research, recruitment and education, maintaining an

> adequate base of talent, and sustaining critical infrastructure for research and experimentation. One critical area requiring support by ONR is the "knowledge infrastructure" in Naval Architecture and Marine Engineering.

National Research Council, *An Assessment of Naval Hydromechanics Science and Technology,* 2000

As is apparent from the title, this study focused on one important aspect of naval engineering: hydromechanics. In this study the following statement appears:

> 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.

The committee restated the objectives of the NNR-NE and then stated the following:

> The assumption of national responsibility for the support of a research area requires the long-term commitment of a significant level of investment.
>
> 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 system relies partially on funding made available from major acquisition programs, which in turn produces dramatic variations in the funding for naval research.
>
> 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.

U.S. Department of Commerce, *National Security Assessment of the U.S. Shipbuilding and Repair Industry,* 2001

This study, centered as it was on the shipbuilders, largely confined itself to the needs of those facilities to improve the process of construction. The historical focus of the National Shipbuilding Research Program (NSRP), referred to below, has been on improving the competitiveness and process efficiency of U.S. shipbuilders. The report states the following:

> A key reason for U.S. warship superiority has been the shipbuilding research and development (R&D) expertise that currently resides . . . [in] the Navy's laboratories, acquisition commands and certain shipbuilders and universities.
>
> An existing effort to bolster the shipbuilding R&D infrastructure is the National Shipbuilding Research Project Advanced Shipbuilding Enterprise (NSRP ASE). The U.S. Navy and the 11 major shipbuilders that comprise NSRP are jointly funding R&D costs.

The report's conclusions did not address R&D.

Transportation Research Board, *Naval Engineering: Alternative Approaches for Organizing Cooperative Research,* 2002

This report concentrated on the evaluation of alternative structures for the management of research and used the current ONR principal investigator model as the baseline for comparison. Three alternative models were considered, and committee members strove to assess how well the varied management structures would perform R&D that supports Navy needs. The evaluations of the three alternative structures were not based on the evaluation of actual enterprises. The following excerpts are from the study:

> The Navy is facing serious limitations related to an adequate supply of the creative talent and knowledge base needed. ONR also lacks sufficient personnel with broad, interdisciplinary experience. ONR stressed the importance of an approach to research that incorporates total systems aspects of the naval

> engineering discipline. . . . The committee was able to describe and evaluate only the alternative organizational models that were presented to it and that are the leading contenders for consideration by ONR.
>
> ONR has two overall goals that it needs to achieve in adopting a model for naval engineering cooperative research: (a) to maintain and develop human capital and (b) to revitalize naval engineering and improve ship design and production.
>
> Naval engineering graduates and practicing professionals need to approach ship design, development, and production/construction from the "total ship" point of view in order to meet the challenges of the future Navy. Hence, the concept of "total ship engineer" must be infused into the education and professional development of future naval engineers.
>
> With regard to the second ONR goal, there is a critical need for the U.S. ship design community to revitalize its ability to accomplish creative new research and to support higher-performing, cost-effective designs and more innovative ship systems engineering. In addition, research results need to be transferred to the next stage of technology development and used in actual ship designs.
>
> Organizational models considered: individual principal investigator (current practice); professional society/community of practitioners model; consortium model; project-centered model.
>
> The committee found that all three models for cooperative research organizations that it evaluated are capable of meeting all of ONR's program objectives. No specific cooperative model was recommended.

An interesting feature of this study is the significant and repeated emphasis on "total ship" methods, approaches, and education. This appears to be consistent with the recognition that more than research is necessary to stay at the forefront of knowledge in specific scientific fields: it is essential to develop and keep healthy the national ability to pull knowledge together as needed to support the design of the large, complex structures that are Navy ships. The marrying and integration of technologies are at least as important to the final result as are the technologies themselves.

5

Conclusions and Recommendations

The Office of Naval Research (ONR) asked the National Research Council (NRC) to examine the state of basic and applied research in the scientific fields that support naval engineering and to advise it on whether ONR activities, under its National Naval Responsibility for Naval Engineering (NNR-NE) initiative, have been effective in sustaining these fields. The study committee was also to identify opportunities to enhance innovation, research, and graduate education in these fields and identify areas of scientific research that provide opportunities to make fundamental advances in naval ship capabilities.

The committee's conclusions and recommendations are presented in five sections: the justification and value of the NNR-NE; the state of science and technology (S&T) supporting naval engineering; the completeness and balance of the NNR-NE portfolio of basic and applied research; opportunities for enhancement of research and graduate and postdoctoral education, and related institutional and physical infrastructure; and, finally, the effectiveness of the NNR-NE initiative. Recommendations are addressed to the administrators of the NNR-NE initiative and of ONR. Several of the recommendations that concern scientific research opportunities could be acted on within the present structure of the initiative. Recommendations for measures to increase the effectiveness of NNR-NE and to enhance innovation, research, and graduate education through changes in management processes would require action by senior ONR administrators.

NEED FOR AND VALUE OF NNR-NE

Need for Navy Support

Research provides the fundamental technology and knowledge that ensure Navy success in future operations. Within the Navy's research portfolio are basic and applied research programs that provide advances in knowledge and technology and lead to future naval capabilities. Some of the basic and applied research used by the Navy is supported by the Department of Defense (DOD), the National Science Foundation (NSF), the National Institute of Standards and Technology, and other agencies. However, some basic and applied research is so specific to Navy needs that it is supported only by the Navy. Without Navy support the research would not be performed. NNR-NE was created to support such research. Navy support is necessary for basic and early applied research programs that

- Are in fields critical to naval engineering that would not make progress without Navy support,
- Have a long-term horizon (i.e., programs that expect to yield progress on fundamental problems over a 10- to 20-year period), and
- Have potential for broad application and for discovery of knowledge that may lead to advances in naval capabilities.

Navy support for NNR-NE research is critical for several reasons. Technological progress is essential to security to ensure that naval superiority is maintained as the operating environment, missions, and resources available to the Navy change in the future. The history of innovation in ship design and development provides examples of cases in which basic and early applied research in fields related to naval engineering was essential to the development of new naval capabilities. Moreover, the potential exists for high-payoff applications of research in progress today, even if the probability and form of applications cannot be predicted precisely. Finally, in areas where improvements in ship design and capability have been slow (e.g., innovations that aid in cost control), it is likely that lack of innovation can be attributed, in part, to past lack of support for basic research.

Navy support for NNR-NE is also valuable because DOD funding of basic and applied research historically has yielded benefits beyond national defense and DOD is a primary funder of research and graduate education in a number of engineering disciplines of importance to the U.S. economy. Without Navy support, the critical mass of technical expertise and research talent in these fields would not be maintained, and the capability to innovate in naval engineering would be lost in the United States.

Value of NNR-NE

> **Conclusion 1:** The NNR-NE, as defined in the 2001 ONR memorandum establishing it and the ONR instructions defining the NNRs in general, is a useful means of organizing ONR support of basic and applied research in the scientific and technical fields that underlie naval engineering.

Assigning the NNR designation established Navy policy that the identified activities are deserving of special consideration in planning and budgeting at ONR and that the activities are to be coordinated to sustain U.S. research capability to work on problems important to the Navy, maintain the supply of scientists and engineers in disciplines of unique Navy importance, and ensure that ONR can continue to provide the S&T products necessary for naval superiority. The NNR-NE designation is intended to establish naval engineering as an ONR priority, define ONR objectives in naval engineering, and create a management structure for integrating a diverse group of basic and applied research programs with education and outreach activities. ONR's naval engineering activities need these three elements—high priority, clear objectives, and effective management.

ONR has designated four fields as NNRs: ocean acoustics, underwater weaponry, undersea medicine, and naval engineering. Among these fields, the need for NNR designation is arguably the greatest for naval engineering. Management of research in the other three fields is simpler, because each has a relatively narrow focus and the research objectives and research community to be sustained are relatively easy to define. In contrast, naval engineering is an essentially integrative activity that must apply scientific knowledge from an expansive array of disciplines to solve multiple complex problems of naval ship design. Therefore, the attention to long-term planning and research coordination that the NNR process calls for is critical for producing naval engineering innovation.

HEALTH OF THE S&T ENTERPRISE SUPPORTING NAVAL ENGINEERING

The committee examined the state of research, education, and physical and institutional infrastructure in the fields supporting naval engineering identified by ONR as within the scope of NNR-NE: ship design tools; structural systems; hydromechanics and hull design; propulsors; automation, control, and system integration; and platform power and energy. Because of the breadth of the relevant scientific fields and the constraints of the study's schedule and resources, the committee does not regard its assessments as definitive. The committee's recommendations propose a process for monitoring the health of these fields systematically so that ONR can obtain the information it needs to guide sound research investment decisions.

State of Research

The committee's conclusions address the status of the research enterprise in the scientific and technical fields supporting naval engineering as these fields are pursued in universities, government laboratories, and industry. The committee defined the health of research in a field in terms of the three kinds of research outputs intended from ONR's S&T investments: knowledge, transitions, and people (ONR 2009, 4). A healthy research field was defined as one that is productive in advancing fundamental knowledge, has strong linkages to engineering practice as evidenced by the transition of discoveries to applications and by the existence of effective channels of communication between researchers and practitioners, and has positive prospects as evidenced by the development and retention of talented researchers and by the attraction of new researchers and resources. Typically, in a healthy research field, diverse topics are under investigation, many research methods are in use, and the resources allow ample opportunity for creative research and for the pursuit of transition opportunities. The ultimate success of research depends on the availability of practitioners who are aware of the latest scientific developments, who are proficient in the latest techniques, and who maintain close communication with the research community.

> **Conclusion 2:** Some of the fields within the NNR-NE derive strength from a breadth of related applications. These fields benefit from a

> diversity of funding sources and opportunities for cross-fertilization among communities of researchers working under different sponsorship. For example, vibrant research communities are devoted to computational fluid dynamics and to structural materials and systems.

In these fields, the tasks for the NNR-NE initiative are to ensure that the Navy takes full advantage of the broad pool of researchers that could contribute to solving its high-priority problems and to fund basic and applied research on specific problems relevant only to Navy applications. Mechanisms for these purposes may include better marketing of ONR support opportunities and establishment of more structured interactions with other sponsoring agencies.

In other NNR-NE fields or subfields (e.g., propulsors and naval hydrodynamics), ONR and other Navy agencies are nearly the only sources of support. If the Navy were to identify an urgent need to expand research related to naval problems in these fields, the pool of researchers qualified to work immediately on such problems and not already occupied with Navy-sponsored research would be small. ONR has great responsibility for sustaining education and the institutional infrastructure in these fields. Because of the differences among NNR-NE disciplines, ONR activities to fulfill its NNR-NE obligations need to be tailored to the status of each field.

Hydrodynamics and Hull Design; Propulsors

> **Conclusion 3a:** The major supporters of hydrodynamics basic research in the United States historically have been the Navy, NSF, and the National Aeronautics and Space Administration (NASA). NSF supports a diverse and substantial program of basic and applied research in fluid mechanics, including projects that have potential applications ranging from chemical engineering to robotics to medicine, but few address hydrodynamics problems of likely relevance to naval engineering.

The field of naval hydromechanics, that is, research aimed at understanding the physical phenomena that determine the hydrodynamic and hydroacoustic performance of naval ships, arguably would not survive without Navy support. The move in recent years to replace experimental work with computation—in part to save costs (and time)—has not yet achieved the ultimate potential savings and has in fact created new demands for experimentation and measurements to provide the necessary validation and calibration of codes and models. Given current resources and objectives, the current mix of U.S. naval hydrodynamics basic research (primarily, the ONR program) may be the best that can be achieved to meet narrowly focused needs. However, the overall program is stretched thin and will not be able to meet unanticipated critical Navy needs. More important, it does not have sufficient depth in more basic investigations to generate the breakthrough and disruptive technologies that could redefine naval engineering in the future.

The balance between computational and experimental work in hydrodynamics must be carefully monitored. Experimental validation remains an essential step in the development of hydrodynamic models. However, experiments are costly and therefore more vulnerable during periods of budget pressure. Experimental facilities depend on funded research for their support and without use will deteriorate. Major research facilities are maintained and used at the Naval Surface Warfare Center, Carderock Division (NSWC-CD), and elsewhere, primarily at universities.

Structural Systems

Conclusion 3b: U.S. industry supports little naval structures research because few large commercial ships are built in the United States. Naval structures research is performed and funded in the commercial sector in such countries as Japan and Korea, where commercial shipbuilding is a major industry. Basic research in structures and structural materials (that is, research not focused on naval applications) has a broad range of potential applications and receives support from multiple public sources (including NSF and NASA) as well as private-sector sources; therefore, many structures researchers are working in the United States who could perform naval structures research if they received funding from ONR. However, the health of the field of structures research directly related to naval engineering, exclusive of ONR activities, can only be considered as poor to fair in the United States.

Ship Design Tools

Conclusion 3c: Little research in the United States is aimed at developing improved tools and methods for use in the early stages of the design of naval ships.

In the early design stages, the performance requirements for the new ship must be translated into a viable design concept, and the design is defined up to the level of detail required for making cost and construction schedule estimates (contract design). Decisions made at the early design stages determine the basic architecture of the ship and ship systems and costs of construction and ownership.

At the same time, the shipbuilding industry, with Navy support, has invested significantly in the development of tools for detail design, the stage of design that produces the plans and procedures that guide the shipyard construction workers and provides control over construction cost and schedule. These shipyard design tools are more advanced than are those in use for commercial ship design and construction, because the complexity of modern naval ships demands more sophisticated methods.

The advanced shipyard design tools have potential uses throughout all stages of design. Some recent acquisition programs have applied integrated product and process development, an approach to ship design and construction in which the early design stages are integrated with construction planning to improve the efficiency with which performance and cost objectives are met. However, broader use of shipyard design tools and databases in this manner may be hindered because there has been little transition of the technology developed by private-sector shipyards to Navy ship designers, many advances are regarded as proprietary, and the level of detail in associated databases is often not compatible with the early-stage analysis of alternatives and set-based design for new concepts.

The NNR-NE portfolio does not include investments in detail design tools because development of these tools is not considered to be basic research. In general, research in ship design tools tends to be focused on the transition of basic research knowledge gained in multiple disciplines to design applications; hence, it is often perceived as applied research and may receive low priority in programs oriented toward basic research.

Nonetheless, there are basic research opportunities associated with generic technologies such as systems engineering, multidisciplinary optimization, set-based design, efficiency and accuracy of solvers, physics-based modeling, and multiphysics coupling techniques. These opportunities are particularly relevant for advanced ship concepts where there is often a lack of existing rules-based methods and experimental data and existing tools have not been verified, validated, or accredited for use. Because basic research on ship design tools has a limited range of potential applications and receives meager support from government and private-sector sources, few researchers in the United States are predisposed to perform such research even if increased funding in the field were available from ONR.

Ship design tools research is actively pursued in the commercial sector in Asia (where commercial design and shipbuilding are thriving competitive industries) and in Europe. The focus in these markets is on large product carriers, containerships, passenger ships, and offshore vessels and platforms, and therefore the research has limited applicability and little opportunity for transition to naval combatant ship design. However, the international design industry has produced tools with potential application to early-stage naval ship design.

Automation, Control, and System Integration

> **Conclusion 3d:** Research in automation and control receives significant support from NSF and from DOD. Both agencies support basic research, and DOD is the major supporter of applied research. NASA has supported work in this area in the past.

Basic and applied research in automation and control outside ONR appears to be strong in terms of funding and numbers of researchers. In general, controls, embedded systems, and automation are relatively well-funded topics in engineering research today. This activity includes research relevant to naval systems. The evident ONR niche in the field is application to very specific Navy requirements (e.g., robotic underwater vehicles). System integration has fewer researchers but is funded by government agencies in addition to the Navy. As with automation and control, the principal Navy-specific problems appear to be application to special needs.

Platform Power and Energy

> **Conclusion 3e:** Ensuring efficient transition of new power and energy technology to the designers and builders of Navy ships is an urgent concern.

Power and energy technology is a dynamic field driven by developments in computing, telecommunications, and power electronics for industrial, consumer, and grid applications. Research and development in power systems is conducted and funded by industry, the Department of Energy, NSF, and DOD. DOD, and in particular the Navy, has been among the leaders in the funding of research to support design of power systems of up to 100-MW capacity matching Navy needs. Research on land-based systems can be expected to make a major contribution to components and subsystem technologies that meet the Navy's special power system requirements. The Navy seeks to develop power and energy systems for ships that will be equipped with electric drives and with electrically powered weapons, high-power radars, and electrical components replacing hydraulic systems. Because future shipboard systems will be of small physical dimensions and have power demands far exceeding the available onboard generation, the problems and possibilities for ship-based power system control and energy storage differ significantly from those for land-based systems. Each weapon and radar system will not be able to bring its own power system on board, and the future ship power system will be different from that of the past.

Monitoring the Health of the S&T Fields That Support Naval Engineering

> **Recommendation 1:** To fulfill its obligation under the NNR-NE to sustain U.S. research capability to work on problems important to the Navy, ONR should carry out regular systematic assessments of the state of health of each of the research fields supporting naval engineering in the United States.

ONR assessments should examine the objectives and progress of related research supported by ONR, other DOD agencies, other federal government agencies, and the private sector. The examination should include research in each field that is supported by non-Navy sources and motivated by the potential for applications outside naval engineering but that may constitute a pool of expertise and facilities that could be brought to bear quickly on problems important to the Navy, if support were available and researchers were induced to work on naval engineering problems.

Judging the relevance of current work in each field to the Navy mission should be part of the assessments.

The most meaningful measure of the health of research in the fields supporting naval engineering is evidence of technology-driven improvement in ship performance and cost. Therefore, as part of its monitoring of the health of these research fields, ONR should evaluate U.S. and worldwide innovation in naval engineering practice. ONR's international connections through the participation of foreign institutions in sponsored research in the NNR-NE will be valuable as a source of information about worldwide developments. The evaluation should look beyond ONR's own programs (*a*) to ask whether progress in performance is being made (according to recognized measures such as match to threats, cost, and survivability) and (*b*) to determine the sources of the technologies that allowed progress.

State of Education

Training of Future Researchers

> **Conclusion 4:** The U.S. graduate education establishment that conducts research and trains future researchers in the NNR-NE fields draws strength from the diversity of the S&T disciplines engaged. However, research centers and departments concentrating on certain specialized fields critical to naval engineering and deriving a large share of their research support from ONR (including centers and departments that perform research in hydrodynamics and in ship design methods) may be vulnerable. A decline in research support for these fields would cause these departments to diminish or disappear. Critical research capabilities would be lost, and the supply of future researchers would be interrupted.

Professional Education

> **Conclusion 5:** The Navy recognizes that providing for the development of future naval engineers is essential to its mission. ONR has initiated outreach programs to attract new students to the naval engineering disciplines, but they are limited in scope and resources given the needs. The recently funded Naval Engineering Education Consortium may prove to be of value in recruiting and developing students in naval systems engineering.

The supply of engineering graduates for professional and research careers in naval engineering is constrained by citizenship requirements. Persons who are not U.S. citizens have difficulty in obtaining permanent residency even with advanced degrees and training in needed disciplines.

Current initiatives are useful to the Navy in attracting new students into naval engineering and maintaining an adequate pipeline of capable researchers for the future, but the resources devoted to those initiatives are limited, and vigilance will be necessary to ensure that Navy needs continue to be met.

> **Conclusion 6:** Few graduate professional engineering programs in the United States provide multidisciplinary education focused on naval engineering problems. While more than 20 colleges or universities offer programs having some link to maritime, naval, or ocean engineering at the undergraduate level, only 12 offer a naval engineering course of study at the graduate level. Graduate programs with strong multidisciplinary components are the most promising setting for development of the knowledge and skills required to carry out the essential integrative function of naval engineering.
>
> **Recommendation 2:** ONR should make a special effort to encourage multidisciplinary graduate programs focused on naval engineering that train future researchers and professionals.

State of Infrastructure

The committee understood the reference to infrastructure in its task statement to mean institutional as well as physical infrastructure. Institutional infrastructure was defined as the established institutional framework of research in naval engineering—schools; university, government, and industry research laboratories; grant-making organizations such as ONR and NSF; and scientific and professional societies. Physical infrastructure was defined as the structures and equipment required to carry out research in the naval engineering–related fields, for example, towing tanks, wave basins, and cavitation flow tunnels for experimental hydrodynamics and structural test facilities.

Institutional Infrastructure

The committee solicited views on the state of the scientific and technical institutions critical to naval engineering from researchers; educators; the Naval Sea Systems Command (NAVSEA); and U.S. and foreign commercial ship designers, builders, and operators. The four participants in naval engineering S&T are the Navy, the private-sector shipbuilding and ship design industries, commercial ship operators, and the research universities and other independent research organizations. The responses that the committee received from this community indicate the following:

- Commercial shipbuilding is focused on efficiency and cost (one concern of the Navy). U.S. industry investment in offshore technology is strong, and industry demand for marine professionals is vital in supporting the maritime-related university infrastructure and human capital pipeline.
- The activity of the international research community in major shipbuilding countries such as Japan, Korea, and Norway (a center of the offshore industry) is isolated from U.S. interests and efforts.
- U.S. universities are a rich source of expertise that potentially is applicable to Navy problems but is not fully utilized by the Navy now. For example, there is little overlap between the list of researchers receiving support in NSF's fluid mechanics program (NSF 2010) and NNR-NE hydromechanics research grant recipients, and ONR management expressed concern that ONR grant opportunities have not always been publicized as effectively as possible.
- The U.S. government is overwhelmingly the major supporter of relevant research; within the U.S. government, the Navy is the largest supporter, and within the Navy, ONR.

The ability of the naval laboratories and government R&D facilities to support the naval ship systems engineering S&T infrastructure is varied. The results of the committee's assessment indicate the following:

- NAVSEA's NSWC-CD is the primary facility conducting research and development for transitioning NNR-NE research results to naval applications.

- NSWC-CD has been effective in supporting advanced degrees in naval engineering; in recruiting naval engineers; and in promoting science, technology, engineering, and mathematics (STEM) education.
- NAVSEA's Naval Undersea Weapons Center has relevant but limited activity in unmanned vehicles and in system integration (focused on energy sources).
- The Naval Research Laboratory's diverse mission does not emphasize investments in the NNR-NE fields.
- Although NSF sponsors basic research in related areas (including fluid dynamics, structural materials, energy and power, and systems engineering), the projects are heterogeneous and rarely address problems critical to naval engineering progress. Similarly, the Defense Advanced Research Projects Agency (DARPA) and other DOD agencies support relevant research, but rarely with potential naval applications or specific Navy needs in mind.

Physical Infrastructure

> **Conclusion 7:** The committee collected limited data on physical research infrastructure from ONR, Navy laboratories, and naval engineering researchers. No obvious shortfalls were identified. The existing infrastructure at government, university, and private research laboratories appears to have been adequate for the needs of current Navy research programs. Improvements in computer technology and equipment have benefited research in areas such as real-time physics-based simulations.

DOD's Defense University Research Instrumentation Program, which awards competitive grants for acquisition of major equipment, has helped maintain naval engineering research facilities.

> **Conclusion 8:** Because the content of ONR's research portfolio is strongly influenced by researcher proposals, infrastructure needs for the portfolio tend to be determined by availability. Maintaining and funding test facilities are challenges. Facilities rely heavily on fees collected from users conducting government-sponsored research; therefore, if research funding is interrupted, survival of facilities is jeopardized.

The committee calls the attention of ONR to the 2000 report of the NRC Committee for Naval Hydromechanics Science and Technology, which noted that these facilities require ongoing investment to update instrumentation and strong technical support staffs to produce cutting-edge research (NRC 2000, 3).

WHOLENESS OF THE NNR-NE PORTFOLIO

The task statement directs the committee to "assess the wholeness of the program and, as appropriate, identify any key opportunities for the Navy to make fundamental leaps in sea platform capability and affordability." The study also is to assess whether the technical areas included within ONR's definition of NNR-NE adequately define its scope.

The first section below presents the committee's overall conclusions concerning the wholeness of the NNR-NE research portfolio and the definition of the scientific and technical areas included within it. The second presents conclusions about the portfolio of research projects in each of the technical fields that ONR includes within its definition of NNR-NE.

Overall Portfolio

Relationship of the Portfolio to Needs and Objectives

> **Conclusion 9:** The wholeness of the NNR-NE portfolio can be judged only by comparing its objectives and accomplishments with the Navy's priorities for innovation in naval engineering. Priorities should be determined through regular communication with ship designers, fleet strategic planners, and researchers in the fields allied with naval engineering and should be specified in a plan. Definition of the focus and expected value of NNR-NE basic research would be elements of such a plan. Planning is necessary in managing an applied research program and is not inconsistent with the spirit of basic research. The committee is not aware of a plan for guiding basic and early applied research in the naval engineering–related fields that is specific enough to fulfill this need.

The committee concurs with the findings of the 2005 NRC Committee on Department of Defense Basic Research that basic research in DOD should include studies aimed at "discovery arising from unfettered exploration" as well as "focused research in response to identified DOD technology needs" and that unless a clear understanding of the expected value of a basic research program is communicated to DOD leadership, long-term support of the research will be unlikely (NRC 2005, 3–4). In the case of NNR-NE, the importance of focused research within the basic research portfolio may be especially great.

The committee concurs also with the 2005 NRC committee's conclusion that "DOD should view basic research, applied research, and development as continuing activities occurring in parallel, with numerous supporting connections throughout the process" (NRC 2005, 2). Therefore, to ensure the wholeness of the NNR-NE portfolio, ONR will need to identify the implications of DOD technology needs for basic and applied research priorities. A clear correlation between needs and research emphasis was not always evident to the committee in its examination of the NNR-NE portfolio and its review of the research needs implications of the Navy's operational challenges.

Definition of the Technical Areas Within NNR-NE

In presentations and in project summaries provided to the committee, ONR management defined the scope of research within the NNR-NE to include basic and early applied research in six scientific and technical areas that support naval engineering: ship design tools; structural systems; hydromechanics and hull design; propulsors; automation, control, and system integration; and platform power and energy. The task statement indicates that "the study will assess whether these seven disciplines adequately define the scope of NNR-NE." (The task statement lists hydromechanics and hull design as two distinct fields, refers to ship propulsion rather than propulsors, and does not refer to platform power and energy.) To respond to this part of its charge, the committee considered the practical implication of including each field within the scope of NNR-NE; that is, that fields within an NNR are to receive active Navy stewardship because they are essential to the Navy and unlikely to receive support elsewhere. The committee's conclusions concerning the definition are as follows:

- Advances in all six of the areas could contribute to innovation in ship design.

- The committee does not see evidence that any of the six fields is "mature" in the sense that the field is unlikely to produce future advances that would contribute to ship design and performance.
- Each of the fields, if broadly defined, receives support from sources other than the Navy and has application beyond naval engineering, but the need to maintain scientific expertise in the special problems of unique importance in naval engineering justifies including each of the fields within an NNR.
- Power and energy provision will be a critical design problem for future naval ships; therefore, this field should remain a part of the NNR-NE. The committee understands that ONR basic and early applied research in power and energy may not be managed in the ONR division that houses most of the NNR-NE fields. The definition of NNR-NE should not be dictated by organizational arrangements within ONR.
- The major gap in the present definition is inadequate acknowledgment of the need for basic and early applied research to support the integrative function that is central to the practice of naval engineering. The present portfolio in automation, control, and system integration does not appear to fulfill this need, and ONR needs a new vision to guide research in these areas. Realizing the ultimate potential value (in terms of contribution to the Navy mission) of a research breakthrough in any one of the six fields in the present NNR-NE definition usually depends on advances in other fields. ONR basic and early applied research should provide an understanding of the relationships among the fields. Without an integrated multidisciplinary approach, there are likely to be omissions in basic and early applied research and incorrect projections of the course and speed of technology development; that is, capabilities will not be available when needed.

Recommendation 3: ONR should retain the six fields of ship design tools; structural systems; hydromechanics and hull design; propulsors; automation, control, and system integration; and platform power and energy in the definition of the areas of basic and applied research within NNR-NE. The definition should state that all ONR basic and early applied research in these fields is to be coordinated to meet the goals of the NNR-NE. In particular, basic and early applied research in platform power and energy should be retained in the

> definition regardless of where this activity is housed in ONR. In addition, the definition should explicitly identify multidisciplinary systems engineering as an area of basic and early applied research within NNR-NE.
>
> **Recommendation 4:** The Navy should dedicate an important share of its resources for naval engineering S&T to problems whose solutions are expected to have broad applicability to a range of possible future ship programs.

The latter recommendation is consistent with the ONR Discovery and Invention Portfolio's objective of providing the Navy with technology options (ONR 2009, 26) and with the long-term perspective that the NNRs are intended to take. It also is consistent with the recommendation of the 2005 NRC Committee on Department of Defense Basic Research that DOD should define basic research not as research that is designed with no specific applications relating to the Navy mission but rather as research with the potential for broad rather than specific application (NRC 2005, 1).

Research Portfolio in Each NNR-NE Technical Field

The committee reviewed the topics of ONR-funded projects in 2006–2009 in each of the NNR-NE fields, received presentations from ONR program officers on objectives and accomplishments in each field, and received presentations from ONR-sponsored researchers. The committee did not review the content or quality of the products of individual research projects. The committee's assessment of the portfolio was not definitive because of limitations on study resources and on the information that ONR was able to provide the committee on content and output metrics. For the same reason, recommendations concerning research priorities are offered below only in selected areas where the need appeared clear.

The committee considered three aspects of the research projects in each field: intellectual quality, mission alignment, and management commitment and resource adequacy. On the basis of this review, the committee reached the following conclusions with regard to the six research fields:

> **Conclusion 10a:** The research portfolios in some of the fields (including power and energy and structural systems) appear to be of high

> intellectual quality, organized around well-defined objectives, demonstrating progress, aligned with mission needs and potential applications, and adequately supported.
>
> **Conclusion 10b:** For other fields (including automation, control, and system integration and ship design tools), the objectives are not evident and the project portfolios appear to lack cohesion or to be too narrowly focused. The underlying sources of problems in the less strong portfolios may be traceable to the extent and quality of input from users and the research community in the articulation of research needs and in user evaluations of the research products. Also, in some fields (including ship design tools), relevant research at ONR that is outside the administrative definition of the NNR-NE, and regarding which the committee did not receive information, may address some apparent gaps in the NNR-NE portfolio.
>
> If ONR were to explicitly include systems engineering as a scientific area within the NNR-NE research portfolio, as Recommendation 3 calls for, it is likely that the areas of automation, control, and system integration and ship design tools would gain in focus, that the potential for impact of research in these areas would become more evident, and that they would be more successful in attracting resources. The present NNR-NE definition contributes to the focus on the precise technical challenges in these areas. Under a systems engineering umbrella, it would be possible to integrate all the systems modeling activities in the portfolio.
>
> **Conclusion 10c:** The pattern of funding large numbers of small research projects that is evident in the portfolios of several of the NNR-NE fields suggests a concern that the portfolios in these fields may not be well coordinated toward achievement of a small number of sharply defined goals. A tendency to spread available resources thinly but widely would run counter to the intent of the NNR initiative to ensure that limited resources are concentrated sufficiently to produce results in the most critical fields (Gaffney et al. 1999, 15).

Awards of smaller grants allow ONR to support a larger number of academic departments that provide naval engineering training.

The conclusions of the committee concerning the research portfolio in each of the NNR-NE fields are presented in the subsections below. The final section of this chapter presents a recommendation for ONR conduct of ongoing and systematic evaluations of the portfolios.

Hydromechanics and Hull Design; Propulsors

> **Conclusion 11:** The two principal themes in the portfolio of recent ONR basic and early applied research in hydromechanics and propulsors are (*a*) simulation-based analysis and design capabilities to augment or replace traditional physical test–based approaches and (*b*) targeted research to address high-priority areas in reduction of acoustic and radar signatures, nonacoustic detection, prediction of extreme motions (particularly roll and maneuvering), and prediction of wave impact loads.

A major share of ship-related research is for large-scale computational fluid dynamics. The portfolio also includes a significant commitment to the conduct of prototype tests by complementary efforts at NSWC-CD. The commitment to testing seems healthy and indicates that ONR recognizes that progress requires a balance between experimental and computational work. Propulsor modeling has a much higher profile than a decade ago, with emphasis on crash-back maneuvers. Several investigators are taking diverse approaches to this problem.

Structural Systems

The following are the evident objectives of the NNR-NE structures portfolio:

- Developing technologies for life-cycle performance analysis and the monitoring of ship structural systems;
- Understanding the behavior of novel ship structures, such as composite and aluminum subsystems, during and after fire to enable modeling and predictions;
- Providing a protection system or armor that can defeat several threats and meet structural and stiffness requirements; and
- Facilitating use of alternative hull forms that are lighter, more survivable, stealthier, cheaper, easier to maintain, and longer-lived than steel or aluminum hulls.

Conclusion 12: Structural systems research places strong emphasis on structural survivability from fire and explosions and on materials other than steel, such as composite and aluminum structures.

Conclusion 12a: In research areas within the portfolio such as fire resistance of composites, blast-resistant polyurea coatings, and fully coupled fluid–structure interaction simulations, there are breakthrough opportunities. The work on isogeometric analysis could lead to a breakthrough in structural and fluid–structure interaction analysis.

Conclusion 12b: In the structural systems portfolio, basic research topics are awarded to academic institutions, and applied research topics are awarded to applied research laboratories such as NSWC-CD, the Naval Research Laboratory, and industry research organizations. The ratio of basic to applied structural systems projects is approximately 2:1; however, ONR's Future Naval Capabilities program also conducts applied structures research. Although budgets are limited, there appears to a balance between new and continuing projects.

Conclusion 12c: Certain structures topics important for naval engineering are not in the portfolio, including coatings and fatigue life extension. These are topics of basic and early applied research in other ONR divisions not included within the NNR-NE definition. Other topics that are relevant to naval engineering but administered outside the division responsible for NNR-NE include bearings and lubrication.

Conclusion 13: Navy plans call for building fewer new classes of ships in the future and sustaining the fleet through production of ships according to modified versions of existing designs. Existing ships will continue in service longer and be subject to modernizations to extend service life. These decisions have implications for the relative importance of research on structures, design tools, and other technical areas within NNR-NE. The committee could not identify research programs in the NNR-NE portfolio that addressed this future need.

Ship Design Tools

Basic and early applied research on problems in total ship systems design is largely missing from the portfolio. The committee is aware that ONR conducts later-stage applied research (outside the scope of NNR-NE) on these problems and conducts some basic and early applied research on these problems outside the ONR Ship Systems and Engineering Research Division (which administers the NNR-NE).

> **Recommendation 5:** ONR should view total ship systems design as a legitimate topic of basic and early applied research, and all such research at ONR should be coordinated through the NNR-NE framework.

The focus and objectives of the design tools portfolio were not evident to the committee. The portfolio includes topics ranging from genuinely basic research to highly applied topics. Moreover, the objectives of the portfolio, as stated in the ONR presentations to the committee, are beyond the resources available and beyond the scope of basic and early applied research. To manage the portfolio, a definition of the relationship of basic research to design tools—that is, the gaps in scientific knowledge that hinder ship design—is required.

ONR did not present data to the committee on transitions achieved from NNR-NE project results to later-stage applied research or application; however, the committee is concerned that the analysis and computation methods developed in basic and early applied research may not be finding their way into the software packages used in design practice.

> **Conclusion 14:** The effectiveness of ONR basic and early applied research in design tools is hindered by the lack of an adequate Navy-wide plan for research and development of design tools. Such a plan would set goals; assign responsibilities among ONR, NAVSEA, and others; and provide for coordination.

Recent workshops sponsored by ONR, NAVSEA, and the DOD Computational Research and Engineering Acquisition Tools and Environments program and organized by the Navy's Center for Innovation in Ship Design (CISD) have taken a step toward defining the Navy ship design process and associated tools, providing objectives for improvement, and identifying actions and research necessary to achieve these objectives. However, a formal connection between the results of the workshops and ONR design tools portfolio management has not been established. CISD offers an excellent environment for bringing together the people who can provide focus and objectives for design tools and should be leveraged for this purpose.

Automation, Control, and System Integration

> **Conclusion 15:** The portfolio in automation, control, and system integration should be growing and dynamic because the increasing complexity of ships is a key technical problem confronting naval engineering. However, the focus and objectives of the automation, control, and system integration portion of the portfolio were not evident to the committee. The portfolio includes some highly applied projects aiming for narrow objectives, but basic research of broad potential applicability to system integration, system engineering, and system architecture appears to be absent.

Assessing the NNR-NE automation, control, and system integration portfolio was difficult for the committee because it did not receive information with regard to work on these topics that is being performed in other units of ONR.

Platform Power and Energy

> **Conclusion 16:** Platform power and energy was not identified in the 2001 ONR memorandum creating the NNR-NE, yet in 2006 through 2009 (the years for which research spending data were provided to the committee) research funding in this area was the largest component of the NNR-NE portfolio, with most funding for applied research projects. The research is aimed at supporting development of components and systems for providing shipboard power of very high capacity compared with historical requirements. The committee understands that the portfolio has now been relocated within ONR.
>
> **Recommendation 6:** To ensure continuity of component and subsystem technology, the Navy should pursue research and development for power and energy systems in partnership with U.S. industry. It is equally important to pay due attention to integration of the power system with the total ship system and to transition of the technology rapidly and effectively to the ship planners. The transition process should be initiated in the early conceptual design stages.

Use of power electronics–based integrated power systems (IPS) to manage power and energy needs and efficiency offers great potential for enhancing the performance of future Navy ships. ONR has correctly defined and pursued a research and development plan for this technology. However, gaps in Navy planning threaten to hinder transition of the technology beyond ONR research and development.

The definition of power electronics–based IPS and the design of its components, including converters, generators, energy storage systems, and design tools for more conventional ship designs and weapon system power loads, are adequately emphasized. However, there is inadequate research and development on the dynamics of future systems, where weapon load requirements may far exceed the capacity of available generation and therefore large energy storage systems will be essential. The integration of power electronics–based IPS into overall ship design is also not adequately emphasized. Attention to this problem is essential if future ships are to accommodate radar and weapon systems that the Navy may wish to use.

OPPORTUNITIES TO ENHANCE RESEARCH AND EDUCATION

Enhancing Research

Conclusion 17: Opportunities exist for offering significantly improved capabilities to the fleet through basic and applied research in the scientific and technical fields supporting naval engineering.

Conclusion 17a: Basic research is needed on the problem of integrating ship systems, and research on components will stay on a productive course only if it is tightly linked to long-term programs of research and development of total ship systems. This need is especially apparent in the areas of power and energy systems and ship design tools.

Conclusion 17b: The future of naval engineering likely lies in incorporating advances from younger and rapidly advancing disciplines. If it is to maintain its relevance, the NNR-NE research portfolio must reflect this trend.

Recommendation 7: In planning the NNR-NE research portfolio, ONR should search for research directions and research topics by identifying both (*a*) emerging scientific and technological developments that hold promise for providing new capabilities or new technology options and (*b*) gaps in fundamental scientific and technical knowledge that are hindering fulfillment of needs identified by the operating Navy. The search by ONR for research direction and topics should be systematized, adequately funded, measured, and incentivized and should be included as part of the organization's and its managers' performance evaluation processes. ONR could produce a valuable list of research opportunities through regular and systematic external consultations with practicing naval engineers, the operating Navy, researchers, and other technical experts, and by documenting and publishing the research topic proposals generated by these consultations.

Research directions emanating from emerging S&T developments are often referred to as technology push, while those emanating from gaps in fundamental S&T knowledge are referred to as requirements pull.

Through its workshops and commissioned papers, the committee received suggestions from researchers on opportunities presented by technology and from practicing naval engineers and naval analysts on technology demands arising from Navy requirements. Future Navy requirements for S&T products will be dictated by three driving forces: the operating environment the Navy may face, the types of operations it may be expected to perform, and the Navy's resource prospects. Examples of research needs arising from these forces are the following:

- Needs arising from the future operating environment:
  - New technologies to reduce ship signatures and more capable radar, as means of defense against future threats
  - Ice-strengthened structural design and cold weather operation of ships, to prepare for an expanded Navy mission in the Arctic
- Needs arising from future naval operations (e.g., to support operations such as counterterrorism and irregular warfare):
  - More versatile platforms for inshore and special operations
  - Unmanned vehicles and the ships to carry and support them
  - Integration of complex systems into ship designs with minimum increase in complexity
- Needs arising from resource prospects:
  - Naval engineering aspects of shipbuilding and ship construction engineering aimed at reducing procurement costs
  - Reduction of life-cycle costs, for example through development of life-cycle cost–benefit models, durable structures, open architecture

features to facilitate modernization, and self-repairing and self-diagnosing systems

The role of NNR-NE is to identify and fill gaps in fundamental scientific and technical knowledge that are hindering fulfillment of these needs.

The following are examples of emerging developments that hold promise for providing new capabilities or new technology options for the Navy:

- Physics-based modeling and simulation and computational mechanics. Advances in this area together with the advances being made in supercomputers and parallel processing will greatly assist ship design. For example, development of virtual prototype designs carried out in a real-time simulation framework will allow trade-off studies to be performed quickly and efficiently;
- Virtual design, testing, and evaluation capabilities for platforms systems and subsystems;
- Application of power electronics–based IPS for managing shipboard power and energy needs; and
- Systems engineering tools capitalizing on advances in fields such as human factors, biomechanics, and biomimicry, which may be applicable to ship design and production problems.

The preceding list illustrates needs and opportunities, but because of the limited scope of the present study, it is not systematic or comprehensive. ONR could produce a more valuable list of opportunities by systematically exploiting the same resources that the committee relied on, that is, by consulting with practicing naval engineers, the operating Navy, researchers, and other technical experts.

Enhancing Education

Conclusion 18: Outreach programs have been successful in interesting students in STEM education and maritime careers. ONR supports the Society of Naval Architects and Marine Engineers (SNAME) in expanding the SeaPerch program (an ocean science laboratory project for middle school students). SNAME and the American Society of Naval Engineers are well positioned to provide leadership and support for these outreach initiatives. However, their efforts are limited by the availability of volunteers and funding.

Recommendation 8: ONR should embrace its role as STEM lead for the Navy and adequately fund and manage STEM activities as part of its S&T portfolio. As part of its STEM activities, ONR, in cooperation with NAVSEA, the professional societies, and industry, should consider the following activities:

- Targeting populations in regions with community connections to naval engineering (e.g., local naval architecture universities, shipbuilders, naval facilities),
- Expanding funding and aiding professional societies and industry in volunteer support for collaborative outreach programs (e.g., the Junior Engineering Technical Society), and
- Using NAVSEA funding of the Naval Engineering Education Center Consortium to support SeaPerch and other initiatives.

NNR-NE EFFECTIVENESS

The committee's task statement provides the following direction: "The study . . . will assess the NNR-NE's progress in the ability to: (l) provide and sustain robust research expertise in the United States working on long-term problems of importance to the Department of the Navy; (2) ensure that an adequate pipeline of new researchers, engineers, and faculty continues; and (3) ensure that ONR can continue to provide superior S&T in naval architecture and marine engineering." The committee's evaluation was not definitive because of the limits of its own resources and because ONR does not have the information system that such an evaluation would require. Conclusions on NNR-NE effectiveness and recommendations on how ONR could establish a management process that would allow systematic evaluation are presented below. Systematic evaluation would reveal opportunities to increase effectiveness.

Overall Effectiveness

The conclusions in this subsection concern the effectiveness of the NNR-NE and factors that influence its effectiveness. In outline, the committee concluded the following:

- NNR-NE meets a Navy need but requires planning and stronger links to users and researchers.

- NNR-NE is not yet recognized within or outside ONR as the focus of naval engineering basic and early applied research.
- ONR does not appear to have conducted the reporting that the 2001 memorandum establishing the NNR-NE calls for.
- The role of NNR-NE in the *Naval S&T Strategic Plan* has not been clearly defined.
- ONR has not defined the practical significance of NNR designation for administration and budgeting.
- Some activities called for in the 2001 memorandum or the 2010 instruction have not been undertaken.
- The scope of NNR-NE functions and responsibilities with respect to education and relevant research outside the Ship Systems and Engineering Research Division lacks clear definition.

Conclusion 19: NNR-NE meets a Navy need but requires planning and stronger links to users and researchers.

The research and educational activities within NNR-NE have been effective in fulfilling the Navy's basic need to sustain S&T in naval engineering–related fields. A diverse research program is supported, and significant numbers of graduate and postdoctoral students are involved. An outreach program is making efforts to attract students into the field of naval engineering at the kindergarten through 12th grade, undergraduate, and graduate levels. The physical infrastructure of laboratories and equipment, which receives important support through ONR research grants, appears to be adequate for current needs.

However, the NNR-NE initiative has yet to reach its potential. In particular, the vision of the 2001 NNR-NE memorandum—systematic and coordinated management of a research portfolio toward attainment of clearly defined objectives—has not been fulfilled. ONR has continued to support important basic and applied research in the designated technical fields, as it did before 2001, but the NNR-NE initiative has not had visibility internally or externally, and the coordination and evaluation steps called for in the memorandum have not been conducted consistently. Reinvigorating the initiative by returning more closely to the letter and spirit of the 2001 memorandum would enable ONR to achieve the purposes of the initiative more reliably and efficiently. Effectiveness would be increased if ONR developed a more rigorous procedure for defining meaningful objectives for research in each of the fields within NNR-NE and measuring progress toward them and if ONR reinforced communications channels between NNR-NE managers and the broad user and research communities.

> **Conclusion 20:** NNR-NE has not yet gained recognition within or outside ONR as the focus of naval engineering research.

ONR created NNR-NE as a mechanism to focus its basic and applied research and education activities in support of naval engineering and to emphasize the importance of technical progress in naval engineering to Navy missions. However, NNR-NE has never attained the intended status. The community of researchers and ONR program managers does not justify or evaluate its efforts in terms of their place in the NNR-NE framework or contributions to meeting NNR-NE objectives. Marketing—outreach to the research community to help attract the best talent and ideas and outreach to sponsors and other stakeholders to ensure that the initiative remains relevant to their needs and maintains their support—is a necessary adjunct to the NNR-NE initiative.

> **Conclusion 21:** ONR does not appear to have conducted the reporting required by the 2001 memorandum establishing the NNR-NE.

Essential to the NNR concept is that a collection of ONR activities is to be managed in a coordinated manner to reach a common objective. The 2010 NNR instruction requires that the responsible department report annually on the execution and progress of the NNR. Regular progress reporting is a necessary step toward ensuring that the elements of NNR-NE are managed as a unified initiative and recognized as the focal point of basic and early applied research in naval engineering. The 2001 memorandum establishing the NNR-NE requires that the progress and impact of the NNR-NE be subjected to an external review every 5 years. The committee did not receive documentation of past progress reports or evaluations of the NNR-NE.

> **Conclusion 22:** The role of NNR-NE in the *Naval S&T Strategic Plan* has not been clearly defined.

ONR's 2009 *Naval S&T Strategic Plan* refers only briefly and generally to the NNRs. The plan states objectives for naval engineering research in such broad terms (e.g., platform survivability, stealth, efficient energy and power systems, "new and novel advanced platform design," reduced total ownership cost of naval platforms) that the document appears to be of limited use to research managers in setting priorities and balancing their programs. Correspondingly, ONR has not taken the initiative to relate its NNR-NE portfolio to the *Naval S&T Strategic Plan* or to communicate the importance of efforts carried out under the NNR to the strategy. This is an essential step in ensuring internal understanding of the critical nature of the NNR-NE and the merits of adequately resourcing the NNR-NE initiative.

> **Conclusion 23:** ONR has not defined the practical administrative significance of NNR designation.

The 2001 memorandum establishing the NNR-NE (ONR 2001) and the 2010 instruction defining the NNRs do not identify the practical consequences of NNR designation, that is, how designation of a portfolio of ONR activities as an NNR is to alter the management or objectives of the activities. ONR was already engaged in all or nearly all of the activities that the 2001 memorandum designated as elements of the NNR-NE when the memorandum was issued. The committee's understanding is that, rather than initiating new programs, the memorandum served as a declaration of policy: assigning the NNR designation indicated that (*a*) the listed activities deserve special priority in planning and budgeting at ONR because the identified S&T fields are critical to the Navy and no one else will support them and (*b*) management of these activities must be coordinated with the declared policy objective in mind. However, this significance of NNR designation is not explicit in the ONR memorandum or instruction.

Actions that ONR could incorporate in the NNR-NE initiative to promote and strengthen naval engineering–related research (and which may not have been required in the absence of the NNR designation) could include periodic evaluations of research output, periodic examinations of the health of the field and of the performance of all Navy programs supporting the field, procedures for giving special priority to the NNR-NE fields in ONR program planning and budgeting, and management arrangements to ensure coordination of all relevant ONR activities toward achieving NNR-NE objectives.

> **Conclusion 24:** Some NNR-NE prescribed activities may not have been undertaken.

The 2010 NNR instruction requires coordination of the NNRs with ONR's Future Naval Capabilities technology transition initiatives and with DARPA. The 2001 NNR-NE memorandum requires ONR to create university–industry–laboratory consortia for fostering naval engineering S&T. The committee was not presented with information on how these requirements have been interpreted and carried out. ONR does not appear to have conducted large-scale field experiments within the NNR-NE research project portfolio, with the possible exception of certain power and energy applied research projects, or to have issued special broad agency announcements to fulfill specific objectives of the NNR-NE, as the 2001 memorandum calls for.

> **Conclusion 25:** The scope of NNR-NE functions and responsibilities lacks clear definition.

The 2001 NNR-NE memorandum and the 2010 NNR instruction are imprecise with regard to how naval engineering–related basic and applied research conducted by units other than the ONR Ship Systems and Engineering Research Division should be coordinated with the NNR-NE and on the scope of educational activities considered to be within the NNR-NE.

> **Conclusion 26:** The committee's assessments of the significance of the research were complicated by the lack of a full picture of ONR work related to naval engineering. Particularly in the fields of ship design tools; structures; and automation, control, and system integration, the committee understands that some relevant basic and early applied research is being conducted in ONR divisions other than Ship Systems and Engineering Research. Coordination of all relevant ONR research toward the objectives of the NNR-NE appears to be missing in the structure of the initiative.

A clear definition of the scope of the educational activities that are to be considered part of the NNR-NE is lacking. The statement of task for this study (provided by the sponsor and accepted by NRC) identifies education of future researchers as an objective of the NNR-NE. The 2001 NNR-NE memorandum and the 2010 NNR instruction also recognize ensuring the supply of researchers as part of the NNRs. However, some provisions of the 2001 memorandum and some descriptions of the NNR-NE initiative that ONR presented to the committee indicate that the scope of NNE-NE may encompass a broader range of educational aims, including STEM education and training of professional naval engineers.

ONR has been assigned primary responsibility for the Navy's contribution to the nationwide STEM initiative. It was recommended above that ONR embrace this responsibility and consider expanding some STEM activities. However, the practical significance of managing STEM as an element of the NNRs is not evident.

The reports and documents listed in the 2001 ONR memorandum in support of the need for the NNR-NE frequently cite concern for the future adequacy of the workforce of practicing naval engineers. Ensuring an adequate professional engineering workforce is a primary interest of NAVSEA, because that command, directly and through its contractors, employs most engineers in the field. However, ONR research grants in naval engineering have an important indirect role in providing the professional workforce. Faculty research funding is essential to the survival of naval engineering professional programs because research ensures the intellectual vibrancy of university academic programs. ONR research investments should be directed according to the value to the Navy of the scientific knowledge they produce, but the connection between research support and professional workforce supply cannot be overlooked.

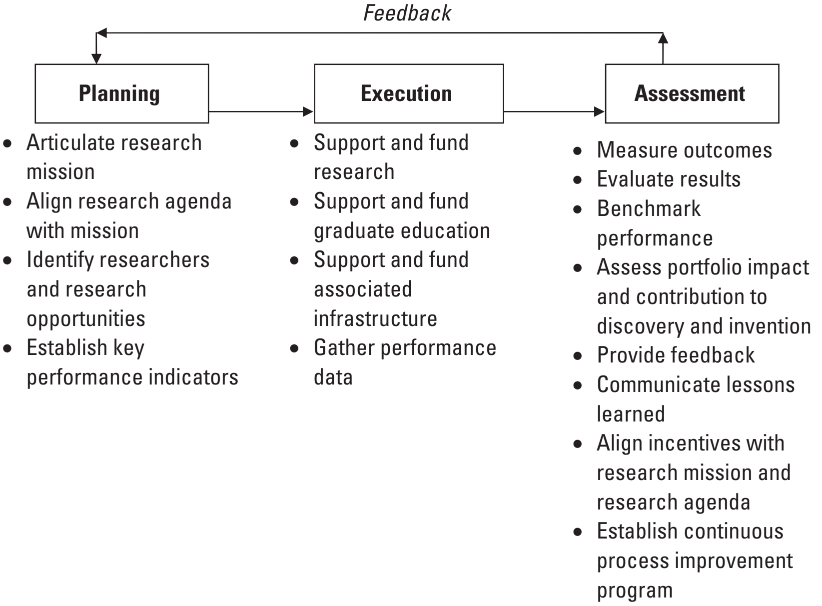
> **Recommendation 9:** ONR should bring NNR-NE in line with the structure of the initiative as envisioned when it was established by taking the following actions:
>
> - **Recommendation 9a:** ONR management should ensure that the elements and objectives of NNR-NE are communicated to researchers, program officers, and research product users and that ONR managers and grant applicants justify new activities within the scope of the NNR-NE by showing how they will contribute to the initiative's objectives.

- **Recommendation 9b:** ONR should develop an enterprisewide information system that will make summary information on NNR-NE research projects readily available to proposers and to ONR's clients, by posting on its website or other means. Summary information should include an abstract, funding, and a contact for each project. Project lists would be an effective way of advertising ONR's interests and funding availability to prospective proposers and would help ONR's clients in the Navy and shipbuilding to stay informed of ONR research.
- **Recommendation 9c:** ONR should use the enterprisewide information system as a management tool in assessing NNR-NE progress; tracking funding allocation trends; benchmarking performance; and communicating NNR-NE progress, achievements, and potential.
- **Recommendation 9d:** ONR should prepare an annual report that compares activities in the NNR-NE for the year with the activities required according to the 2001 memorandum and 2010 instruction and that compares accomplishments with the objectives of the NNR-NE. The annual report should describe how the NNR designation raised the priority and aided the coordination of ONR naval engineering activities.
- **Recommendation 9e:** In revisions of the Naval S&T Strategic Plan, ONR should delineate the expected contributions of the NNR-NE to the plan.
- **Recommendation 9f:** To fulfill the requirement of the 2001 memorandum for creation of consortia to foster naval engineering S&T, ONR should consider adoption of the alternative organizational models proposed by the 2002 NRC Committee on Options for Naval Engineering Cooperative Research (TRB 2002).
- **Recommendation 9g:** ONR should revise the definition of NNR-NE, specifying educational responsibilities and requirements for coordination of naval engineering–related basic and applied research outside the Ship Systems and Engineering Research Division. The definition should specify that all relevant research be coordinated through the NNR-NE, regardless of its location in the ONR organization. Requirements in the 2001 memorandum that have not proved useful should be dropped from the definition.

Increasing NNR-NE Effectiveness

Framework for Research Portfolio Management

High-performance research organizations standardize portfolio management processes on the basis of a series of information search, decision-making, performance, and evaluation tasks. The processes are outlined in Figure 5-1. Planning the NNR-NE includes articulating the research mission, aligning the research agenda with the mission, and identifying researchers and research opportunities. Execution includes supporting and funding research, graduate education, and associated infrastructure and tracking performance indicators. Assessment includes measuring outcomes, benchmarking performance and evaluating results, providing feedback, establishing continuous improvement processes, and publishing lessons learned and best practices. Key to high-performance portfolio management processes are the assessment, benchmarking, and continuous process improvement activities that align incentives with desired performance (Eccles 1991; Eccles and Pyburn 1992; Brown 1996; Melnyk et al. 2004; Reugg 2007; Newell and Simon 1971; Simon 1996; Tan and Platts 2003; Tan et al. 2004).



- Articulate research mission
- Align research agenda with mission
- Identify researchers and research opportunities
- Establish key performance indicators

- Support and fund research
- Support and fund graduate education
- Support and fund associated infrastructure
- Gather performance data

- Measure outcomes
- Evaluate results
- Benchmark performance
- Assess portfolio impact and contribution to discovery and invention
- Provide feedback
- Communicate lessons learned
- Align incentives with research mission and research agenda
- Establish continuous process improvement program

FIGURE 5-1 Framework for research portfolio management.

This management procedure is consistent with the practices that Congress required all executive agencies to follow in the Government Performance and Results Act of 1993 (GPRA) and is related to the Office of Management and Budget's Program Assessment Rating Tool, a parallel initiative to improve executive agency efficiency. GPRA requires agencies to develop performance plans and to measure and report on progress toward goals defined in the plans (GAO 2010, 2–5).

ONR's procedures in the NNR-NE for establishing a research agenda, identifying performers, supporting research, measuring outcomes, and evaluating results are relatively informal. Practices appear to vary by field at the discretion of the program officer. As a consequence, the initiative appears to lack a consistent and rigorous process to define and track performance indicators, assess performance, benchmark outcomes, and achieve continuous improvement.

Conclusion 27a: ONR collects information on a variety of metrics that could be helpful in evaluating progress toward objectives, incentivizing performance, and improving the organization over time. However, it was not clear to the committee that these metrics are linked to a set of measurable objectives for the S&T enterprise in NNR-NE. The committee also could not determine whether any NNR-NE goals or objectives were tied to strategic plans at the department or agency level. The committee was unable to identify an NNR-NE strategic plan that establishes priorities and identifies measurable objectives, an annual performance plan, or performance reports.

Conclusion 27b: The committee could not identify a process by which NNR-NE mission area needs and research strategies are prioritized or a systematic process by which research funds are allocated. Instead, it appears that NNR-NE program officers fund research projects and principal investigators as opportunities arise, without an enterprisewide evaluation process that prioritizes and evaluates research project merit in a consistent manner across the NNR.

Conclusion 28: The committee did not find evidence that NNR-NE measures or achieves balance in its research portfolio, despite its stated balance goal. The committee found no metrics to measure or establish balance in the portfolio. The lack of a metric leads to questions about how such a portfolio could be balanced or demonstrate balance.

Recommendation 10: ONR should establish an enterprisewide strategic planning and assessment process to develop a strategic plan for NNR-NE, link the plan to guiding goals and objectives, communicate those goals and objectives clearly throughout the naval research community, and evaluate and incentivize NNR-NE performance against the strategic plan and objectives. The NNR-NE strategic planning and assessment process should encompass all facets of the NNR-NE mission and should include the following elements:

- *A process to articulate and prioritize NNR-NE mission area needs and research priorities on an annual and continuing basis.* Priorities could be established by following a balanced scorecard or other methodology; the priorities should guide annual and long-term research program funding allocations in a transparent and consistent manner across the NNR.
- *A process for NNR-NE research fund allocation that is aligned with the articulated mission area needs and priorities* so that resource allocation decisions are guided by a transparent, enterprisewide evaluation process that prioritizes and evaluates research project merit in a consistent manner across the NNR.
- *Metrics* for measuring the activities of research needs identification, resource allocation, research management performance, and continuous process improvement.
- *A continuous process improvement activity* that utilizes the metrics to assess research portfolio management activities and alignment with Navy needs and to evaluate and report annually on organizational progress over time.
- *An enterprisewide communication system* to promulgate lessons learned, best practices, and organizational heuristics associated with the NNR-NE strategic planning and assessment process.
- *A research portfolio management procedure* for the NNR-NE as a framework to guide planning and information collection, research administration, and assessment of performance and outcomes. The procedure should follow recognized standards for research portfolio management, including performance benchmarking. The goal of instituting the procedure should be to establish a culture of continuous process improvement.

The enterprisewide strategic planning and assessment process should include the following:

- *A process to develop NNR-NE strategic priorities with respect to connectivity with the wider naval engineering community as well as to communication with stakeholders, technical advisory groups, the user community, and the broader research community.* The process should include adoption of one or more of the cooperative research models reviewed in the 2002 NRC Committee on Options for Naval Engineering Cooperative Research report;
- *A process to identify NNR-NE priorities associated with human capital and organizational development;* and
- *Metrics* associated with connectivity with the naval engineering community and human capital and organizational development.

Recommendation 11: ONR should identify, utilize, and periodically reassess metrics to measure NNR-NE portfolio balance, in line with ONR's stated goals and articulated mission needs. Once established, these metrics should be incorporated into ONR's enterprisewide assessment and continuous process improvement program.

Recommendation 12: As input to the identification of performers, to enhance systematic dissemination of Navy mission and needs, and to improve communications between ONR and operational Navy units, in managing NNR-NE, ONR should utilize mission capability managers who are responsible for understanding specific end-to-end Navy missions (e.g., antisubmarine warfare–antisurface warfare). All program officers should justify their projects in terms of NNR-NE goals, and ONR management should ensure that all aspects of the goals are attended to.

Necessary elements of the recommended process include maintenance of a team of talented and experienced managers, including managers responsible for acting as technology interpreters (as defined below); an internal review process for administrative accountability; arrangements for vertical and horizontal integration of the NNR-NE research portfolio with other related research and development within and beyond ONR; and peer review (as proposed below) for quality control, relevance, and accountability.

Measuring the Output of NNR-NE

ONR uses three groups of metrics as indices of the output of its investments in its Discovery and Invention activities, including NNR-NE: papers published, paper citations, and patents (as measures of new knowledge produced); basic and applied research results that lead to Innovative Naval Prototype or Future Naval Capabilities projects and basic research results that lead to applied research projects (as measures of transitions of results toward application); and numbers of graduate students supported, participants completing degrees, and participants joining Navy laboratories (as measures of contribution to the research workforce). These metrics provide useful information. Trends will indicate whether research is being completed and students are being trained at rates consistent with experience. The transitions measures may indicate the strength of NNR-NE's linkage to ONR's later-stage research and development activities.

However, the present metrics fall short of adequate measures of ONR's investment in NNRs. The transitions metrics are problematic for a basic research program because a basis for determining an acceptable transition "batting average" is lacking. Basic research should be expected to have a low frequency of direct payoffs but often very high value when there is a payoff. Also, basic research can lead to innovation by paths that are indirect and difficult to observe. Papers published and students supported are limited in value as metrics because they correlate with funding levels regardless of the value of output.

ONR should systematically monitor the state of the S&T fields that support naval engineering, in the United States and internationally. The indicators produced by this monitoring would be metrics of the impact of NNR-NE, because the NNR-NE initiative is intended to ensure the long-term health of these fields.

> **Recommendation 13:** As part of the research portfolio management process for NNR-NE, ONR should develop a set of research performance metrics that assess the contribution of its investments to discovery and innovation. In addition to the traditional numbers of publications, patents, and citations, ONR should develop metrics of portfolio impact, discovery, and innovation. These metrics should be inputs to investment decisions in managing the NNR-NE. They also

> should be used to increase visibility and understanding of the importance of ONR naval engineering research investments. Research successes identified through the metrics should be publicized and communicated broadly, and research excellence should be incentivized and celebrated in order to raise the visibility of high-quality research and raise the standard of research quality.
>
> **Recommendation 14:** Because of the importance and complexity of emerging problems in naval engineering S&T, along with increasing demands for integrative and interdisciplinary research across all technological disciplines (NRC 1999), ONR should consider, as part of its continuous process improvement and assessment practices, adopting integrative and interdisciplinary metrics of performance in and across each of the NNR-NE functional areas.

Planning and assessment of a program of basic and early applied research present special problems. Individual basic research projects are inherently high-risk, and the social benefit of the information a project produces may only appear after a long time and through a difficult-to-trace sequence of events. Because of this difficulty, the results of planning and assessment exercises will be imperfect, and determination of useful procedures will require trial and error initially.

However, a major share of the basic research within NNR-NE falls into the category of basic research defined by the 2005 NRC Committee on Department of Defense Basic Research as “focused research in response to identified DOD technology needs” rather than in the category of studies aimed at “discovery arising from unfettered exploration” (NRC 2005, 3). That is, practical problems that the research may help solve are recognized. When the ultimate goal is defined, all research should have a specified relationship to the goal. The 2005 NRC committee also observed that if research managers insist that the value of basic research cannot be measured, institutional support for research will be undermined. Although the value of individual projects is difficult to isolate, the value of basic research can be measured at least cumulatively and retrospectively (NRC 1999, 22), that is, by showing how realized gains in ship performance depended ultimately on basic research. The recommended monitoring of the state of the S&T fields that support naval engineering would provide such a retrospective measure of research impact.

NNR-NE integrative metrics could include, for example, the number of interdisciplinary projects, the number of interdisciplinary publications, impact measures of research conducted within and outside the primary disciplines, citations and funding received outside the primary disciplines, and the numbers of publications and citations within disciplines. Such metrics would encourage program officers and principal investigators to consider and adopt interdisciplinary perspectives in research projects and encourage program officers to look for opportunities for collaboration across naval engineering S&T and across ONR to address critical naval research priorities.

For applied research, appropriate metrics would relate to technology transition into Navy research and development projects at the Budget Activity 3 level and above.

Management of basic research depends primarily on the competence of the program officers, ONR's staff scientists. ONR's expectation is that its program officers "have the appropriate technical expertise and scientific credibility to administer awards and recognize quality—in the marketplace of science and technology, they are the Navy's ultimate smart buyers" (Gaffney et al. 1999, 13). The program officer is required to have "the ability . . . to recognize a promising line of research even before it has been summoned by a formally declared requirement" (Gaffney et al. 1999, 15). The committee's observation is that ONR has such talented program officers overseeing the NNR-NE research portfolio. However, staff with such skills always are in short supply. Formal processes for planning and for selecting research investments are necessary as a backup to the judgment of the program officers, for quality control and management oversight, and to ensure that progress in a field is not disrupted when a talented program officer is not available.

Staff time and funds for overhead activities, such as planning and evaluation, must be expended efficiently. Procedures should be kept simple. Once ongoing collection of the necessary data is established, the burden of periodic reporting and review should be minimized.

Peer Review

ONR's performer evaluation process, including that for its NNR-NE portfolio, differs from that of some other government research sponsors in that it does not include an evaluation of its basic research proposals by external peer reviewers. External review of proposals can be a valuable tool for government agencies that fund basic research, whose impact on future capabilities systems may not become apparent for decades. Organizations that use external scientific peer review for most or all of the basic research they fund include NSF, the National Institutes of Health, and the Office of Research and Evaluation of the National Institute of Justice (NAPA 2009, 67). Within DOD, the Air Force Office of Scientific Research employs a peer-review process using review panels that typically include two reviewers from other DOD offices and one from outside DOD.

> **Conclusion 29:** External peer review (that is, review by technical experts from outside ONR) throughout the research project selection process offers the opportunity to strengthen project selection and to obtain the advice and counsel of technical experts, NAVSEA technical authorities, and industry practitioners who are the ultimate recipients of the developed technology, while maintaining the ONR program officer's independence in making decisions for his or her program.
>
> **Recommendation 15:** ONR should establish a process for NNR-NE (and potentially other programs) in which the program officer assembles a small group of Navy laboratory technical experts (e.g., from NSWC-CD) and NAVSEA technical authorities (who also serve as industry surrogates) to review, assess, and rank relevant proposals received in response to ONR broad agency announcements. The program officer then would be responsible for considering these recommendations and selecting projects. The midproject external review that ONR already conducts would be carried out by this panel with the addition of external reviewers according to the requirements of the present midproject review procedure. The proposal review panel would not remove ultimate responsibility from the program officer. Instead, the panel process would create a dialogue and open lines of communication among ONR and the key Navy constituencies.

Management of the NNR-NE relies primarily on the ONR program officers in the selection of projects and project investigators. Review of research project proposals and investigators before selection does not involve formal external peer review or other formal consultative procedures. Peer review of proposals tends to sustain competition, avoid parochialism, and enhance communication within a research field.

Review by appropriately constituted expert panels would ensure that selection of NNR-NE research projects resulted in a portfolio reflecting both the collective judgment of the research community and the views within the Navy commands with regard to needed technology or strategies. Introducing a wider spectrum of inputs to decisions on the direction of research would speed the application of research results to new technologies of value to users in the design and shipbuilding communities.

The proposed review panels would implement the function of the technology interpreter (described below) in the operation of the NNR-NE. The program officer and the expert panel members would have explicit responsibilities for fostering the technology transition process. Frequent communication would inform the program officer of technologies that the technical authorities need and want and would inform technical authorities of new technologies as they emerge and mature.

Technology Interpreter

ONR today defines the scope of the NNR-NE in terms of six discrete scientific and technical areas that support naval engineering (structural systems; hydromechanics and hull design; propulsors; automation, control, and system integration; platform power and energy; and ship design tools). However, the discipline of naval engineering is essentially integrative. The problem of the naval engineer is to apply the capabilities provided by scientific knowledge in all these areas to the design, construction, and operation of naval ships that satisfy mission requirements, respecting the constraints imposed by human factors and cost considerations.

In recognition of the central importance of integration in naval engineering, ONR should establish a formal role for a technology interpreter in the NNR-NE to provide an institutional focus and mechanism for integrating research, discovery, and innovation in naval engineering. The technology interpreter would be responsible for working with NNR-NE's clients to specify the technology and research implications of their performance requirements and for working with NNR-NE researchers to ensure that their proposals and projects are informed by understanding of the interests of the operating Navy and the constraints of the naval vessel environment.

> **Recommendation 16:** To improve communication of operational requirements and the transitioning of technology to naval ships, ONR should implement the concept of a technology interpreter in the NNR-NE. The task of the technology interpreter would be to assist the technology transition process. The recommended peer-review panels would implement the concept of a technology interpreter in the program officer and technical authority communities. Frequent communication between these communities would inform the program officer of technologies that the technical authorities need and want and inform the technical authorities of new technologies as they emerge and mature. In addition to the review panels, personnel dedicated to improving communications and execution could significantly improve NNR-NE integration with Navy missions, needs, and operational requirements.

The technology interpreter role could be implemented in a variety of ways—as the responsibility of an individual within an ONR department or division tasked with technology interpretation, advocacy, and connection responsibilities; as responsibilities of existing program officers who were encouraged to pursue technology integration within and across their disciplines; or through advisory or consultative arrangements, for example, through peer review or other interactions with contributors outside ONR.

Maintaining Connections Across the Wider Naval Engineering Community

Maintaining connections among the wider naval ship systems engineering community means bridging the valleys that naturally exist between the naval research, design, manufacturing, and operational communities and the commercial and offshore communities. While these communities all share a bond relating to the environments in which they operate, the systems that they build, and the manner in which they are deployed, an innate separation is reinforced by regulations, cultures, values, motivations, and behaviors.

A critical aspect of developing human capital and revitalizing naval engineering is to enable the people who make up that community. Enabling naval engineers requires the following actions:

- Providing naval engineering education;
- Providing naval engineering training to keep the workforce up to date;
- Providing naval engineering mentoring in and outside the workplace, including activities with and through professional technical societies;
- Developing tools, including collection of supporting data and support for verification, validation, and accreditation activities;
- Developing ship design processes, including those for continuous process improvement and technology transition; and
- Developing documentation, including specifications, standards, handbooks, and rules.

The committee did not find evidence that these activities are part of NNR-NE planning, operations, or performance monitoring activities.

Conclusion 30: Connectivity, communication, and human resource and organizational development are important to the success of the naval engineering enterprise. However, the committee was unable to find evidence that NNR-NE strategic planning makes use of measures of connectivity, communication effectiveness, human capital, or organizational development.

Recommendation 17: To maintain connectivity among the wider naval engineering community, NNR-NE should utilize the concept of technology interpreter or otherwise establish integrative and connective responsibilities within ONR management and should continue to support, participate in, and incentivize its ongoing connectivity and communication activities, including conferences, workshops, and seminars, and the activities of ONR Global. ONR should consider adopting additional connectivity and communication activities, including brown bag seminars, scholarly exchange events, and rotation and refreshment opportunities for NNR-NE program officers. The latter should include research sabbaticals at Navy laboratories and academic research institutions and in operational Navy settings.

> **Recommendation 18:** ONR should incorporate human capital and organizational development goals and objectives as explicit responsibilities of NNR-NE during its enterprisewide strategic planning and assessment activities.

Integrating Naval Engineering S&T

The committee found several examples of interdisciplinary and integrative research in the NNR-NE portfolio. The commissioned papers and workshops provided additional evidence of signature integrative and interdisciplinary naval engineering projects, such as the integrated composite mast and a number of materials, hydrodynamics, and ship structures programs. However, the committee concluded that these efforts were the outgrowth of individual program officers or industry representatives who, for personal or professional reasons, engaged in interdisciplinary research and played a key role in developing such programs, rather than the outgrowth of systematic ONR processes that fostered, nurtured, encouraged, or incentivized interdisciplinary or integrative research.

> **Recommendation 19:** As part of its enterprisewide strategic planning process, ONR should establish a culture of interdisciplinary and integrative research within and around the NNR-NE S&T enterprise and should establish processes that foster, nurture, encourage, and incentivize interdisciplinary or integrative research. The NNR-NE interdisciplinary and integrative research objectives should be established as part of the NNR-NE strategic planning processes and should include assessment, benchmarking, and continuous process improvement components.

Developing Human Capital and Revitalizing Naval Ship Systems Engineering

Developing a robust naval engineering pipeline is critical to the development of a robust naval engineering enterprise. NNR-NE efforts in naval engineering S&T workforce development have been sporadic and inadequately supported to date. ONR has also been designated the lead agency for STEM efforts for the Department of the Navy; however, such efforts are considered auxiliary rather than core and critical functional responsibilities.

Recommendation 20: ONR should reinvigorate its efforts in developing the 21st century naval engineering workforce, including improvement of outreach activities to underrepresented groups. ONR's lead role for STEM activities should be strengthened and incorporated into its strategic planning processes, and performance metrics for workforce development and STEM achievements should be identified, measured, incentivized, and included in ONR's assessment, benchmarking, and continuous process improvement activities.

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Abbreviations

GAO	Government Accountability Office
NAPA	National Academy of Public Administration
NRC	National Research Council
NSF	National Science Foundation
ONR	Office of Naval Research
TRB	Transportation Research Board

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APPENDIX A

Presentations to the Committee at Workshops and Meetings

The following presentations were given to the committee at public meetings and workshops. Each presentation may be viewed at www.trb.org/PolicyStudies/NavalEngine21Century.aspx.

MEETING, SEPTEMBER 30, 2009

Survivable Ship Structures, Roshdy Barsoum, Office of Naval Research (ONR)

Computational Mechanics and Signatures, Luise Couchman, ONR

ONR Ship Structural Reliability Program, Paul Hess, ONR

Hull Performance/Undersea Hydromechanics, Ronald Joslin, ONR

Propulsor Hydrodynamics and Hydroacoustics, Ki-Han Kim, ONR

Ship Hydrodynamics, L. Patrick Purtell, ONR

National Naval Responsibility—Naval Engineering (NNR-NE), John Pazik, ONR

WORKSHOP: EXAMINING THE SCIENCE AND TECHNOLOGY ENTERPRISE IN NAVAL ENGINEERING, JANUARY 13, 2010

NAVSEA Perspective on Naval Engineering Needs, Heide Stefanyshyn-Piper, Naval Sea Systems Command (NAVSEA)

Naval Engineering S&T Needs from Perspective of Ship Designer, Robert Keane, Ship Design USA

Naval Engineering S&T Needs from Perspective of Naval Shipbuilder, Larry Dreher, Bath Iron Works

Navy Needs for S&T from a Workforce Perspective, Ronald Kiss, Webb Institute (emeritus)

Navy S&T Needs—Academic Perspective, Michael Bernitsas, University of Michigan

Navy S&T Needs—Academic Perspective, John Leonard, Massachusetts Institute of Technology

Navy S&T Needs—Academic Perspective, Ronald Yeung, University of California, Berkeley

Navy S&T Needs—Academic Perspective, Spyros Kinnas, University of Texas

Navy S&T Needs—Research Community Perspective, Woei-Min Lin, Science Applications International Corporation

Navy S&T Needs—Research Community Perspective, William Milewski, Applied Physical Sciences Corporation

Navy S&T Needs—Naval Shipbuilder Perspective, John Hackett, Northrop Grumman Ship Systems

The Naval Engineering S&T Infrastructure—Navy Labs Perspective, Scott Littlefield, Naval Surface Warfare Center (NSWC)

The Naval Engineering S&T Infrastructure—Navy Labs Perspective, Pierre Corriveau, Naval Undersea Warfare Center

The Naval Engineering S&T Infrastructure—Navy Labs Perspective, Bhakta Rath, Naval Research Laboratory

The Naval Engineering S&T Infrastructure—DoD Perspective, Myles Hurwitz, CREATE Ship, U.S. Department of Defense

The Naval Engineering S&T Infrastructure—Other Agency Perspective, Susan Kemnitzer, National Science Foundation

The Naval Engineering S&T Infrastructure—Commercial Shipbuilding Perspective, Brian Carter, General Dynamics NASSCO

The Naval Engineering S&T Infrastructure—Commercial Ship Design Perspective, Keith Michel, Herbert Engineering

The Naval Engineering S&T Infrastructure—Offshore Industry Perspective, Peter Noble, ConocoPhillips

The Naval Engineering S&T Infrastructure—Industry Perspective, Owen Oakley, Chevron

The Naval Engineering S&T Infrastructure—Class Society Perspective, Kirsi Tikka, American Bureau of Shipping

The Naval Engineering S&T Infrastructure—Commercial Shipping Perspective, Jan Otto de Kat, Maersk Maritime Technology

MEETING, APRIL 6, 2010

ONR S&T Processes, John Pazik, ONR

WORKSHOP: NEEDS AND OPPORTUNITIES IN S&T FIELDS SUPPORTING NAVAL ENGINEERING, MAY 5, 2010

Naval Game Changers, Norman Friedman
Workforce and Education, Ronald Kiss, Webb Institute (emeritus)
National Naval Responsibilities, Kam Ng, ONR
Planning and Priority Setting for Basic Research, Kam Ng, ONR
Undersea Weaponry NNR, Kam Ng, ONR
Potential Technology Implications for the Navy's Future, Ronald O'Rourke, Congressional Research Service
Science and Technology Challenges and Potential Game-Changing Opportunities, Michael Triantafyllou, Massachusetts Institute of Technology

WORKSHOP: NEEDS AND OPPORTUNITIES IN S&T FIELDS SUPPORTING NAVAL ENGINEERING: TECHNOLOGY PUSH AND REQUIREMENTS PULL, JUNE 10, 2010

Researcher Perspectives: Hydrodynamics, Scott Morris, Notre Dame University; Krishnan Mahesh, University of Minnesota; Thomas C. Fu, NSWC-Carderock; David E. Hess, NSWC-Carderock
Researcher Perspectives: Power Systems, Robert Hebner, University of Texas; Steinar Dale, Florida State University
Researcher Perspectives: Structures, Charbel Farhat, Stanford University; Joachim Grenestedt, Lehigh University; Christopher Earls, Cornell University
Transitioning Technology to Naval Ships, Norbert Doerry, NAVSEA
Composites Road to the Fleet—A Collaborative Success Story, John Hackett, Northrop Grumman Shipbuilding
DDG 1000 Human Systems Integration, John Hagan, Bath Iron Works
Research and Technology Challenges and Opportunities (Commercial Ship Design Perspective), Keith Michel, Herbert Engineering; Peter Noble, ConocoPhillips
Naval Ship Design and Construction, Paul Sullivan, USEC, Inc.

APPENDIX B

Abstracts of Commissioned Papers

The committee commissioned nine papers that provide technical, policy, and historical perspectives on issues important to the study. The authors were selected by the committee, and each author was given a topic statement identifying the questions to address.

This appendix contains an abstract of each commissioned paper. Certain papers and their findings are also referenced in chapters of the report. The papers are available at www.trb.org/PolicyStudies/NavalEngine21Century.aspx.

COMMISSIONED PAPER 1

Examining the Science and Technology Enterprise in Naval Engineering: Workforce and Education

Ronald K. Kiss, Webb Institute (May 13, 2010)

The purpose of this paper is to address the topic of workforce and education. The needs for a technically literate workforce and its supporting education system continue to draw the attention of national leaders. A common message has been issued by recent National Academy of Engineering studies, President Obama's April 2009 speech to the Academy, and the November 2009 White House Educate to Innovate initiative: the nation needs to increase its attention to and involvement with the science and engineering education system and the professional development pipeline.

This paper examines the continuum between the naval engineering education system and the workforce that is employed in that profession. A strong relationship exists between activities that attract talent, develop discipline-specific skills, and transition successful naval engineering graduates into the workforce, yet the links between these activities are not fully coordinated. While the naval engineering pipeline exists, there does not appear to be a single entity that is responsible for ensuring that national naval engineering educational needs are being met.

The paper also explores the professional society engineering outreach programs and reviews the current state of undergraduate and graduate naval engineering education. The graduate-level review includes specific programs both in naval engineering and in related disciplines. It examines the naval engineering workforce itself and identifies professional development models and on-the-job training programs to attract, retain, and educate the workforce.

The paper has three sections. One focuses on the undergraduate curriculum, the second on graduate education, and the third on workforce development programs (including engineering outreach programs, industry-specific training, and recruiting efforts to draw talent from related disciplines). The workforce referred to is that needed to meet naval engineering innovation, research, and development needs. Given the significant investment in education and training programs, proper attention must be devoted to retain these skilled graduates in the naval engineering field.

COMMISSIONED PAPER 2

Some Potential Technology Implications of the Navy's Future

Ronald O'Rourke, Congressional Research Service (April 30, 2010)

This paper briefly surveys some potential technology implications of the Navy's future. These implications arise from the Navy's future operating environment, the kinds of operations the Navy may conduct in coming years, and the Navy's prospective resource situation. Each of these subjects is discussed below. The collection of issues discussed in this paper is not intended to be comprehensive, and the issues are not presented in any particular order.

Specific features of the Navy's future operating environment that may have technology implications for the Navy include, but are not necessarily limited to, the following: adversaries with antiaccess weapons;

adversaries with cyberwarfare and related capabilities; adversaries with nuclear weapons; terrorist and irregular warfare threats to forward-deployed Navy ships; limited or uncertain access to, and vulnerability of, overseas land bases; diminishment of Arctic sea ice; and policy-maker focus on energy use and alternative energy.

COMMISSIONED PAPER 3

Game-Changing Ships and Related Systems

Norman Friedman (June 14, 2010)

Naval warfare is shaped by the vastness of the sea, which makes the movements of ships beyond the horizon difficult to know. Thus, relatively small groups of ships have exerted enormous impact, and until the 20th century, all naval battles were fought near important places ashore, because fleets found other fleets as a consequence of blockade operations. The vastness of the sea required large ships for long-range operations. Since those same ships had to come close to land to be effective, a second issue was whether small seagoing craft could tip the balance of naval power against large ships.

This paper is a study of the sources of innovation through the lens of history. Few innovators consciously analyzed the character of sea power and then set out to develop something earth-shaking. Some instinctively grasped the implications of what they were doing. In most cases it is difficult to identify an individual with what is, in retrospect, an obviously decisive development.

The innovations are categorized into three periods, which correspond approximately to types of innovation. The first period, before about 1900, was the era of inventors, of individuals who perceived a broad if unstated requirement and managed to meet it. The second period (1900–1945) was the era of innovation by large naval organizations, which could develop platforms or systems for specific new roles. The third period after 1945 was different because cold war navies were far more integrated into national strategy extending beyond naval operations. Direct effects of naval operations against the land became more important because the probable enemy, the Soviet Union, did not depend on sea transportation. The advent of nuclear weapons greatly confused attempts to understand what the naval game was, hence what innovations were critical. The third period is the current era of system integration, in which payloads often dominate ship design in unpredictable ways.

The issue in innovation is always whether requirements or the innovator (or technology) dominates. During the interwar period, requirements pull appears to have dominated. World War II in effect demonstrated that technology offered new possibilities and thus was worth pursuing independently of requirements.

Overall, the paper takes specific platforms or systems as shorthand for large categories, such as amphibious ships. Some vital technologies cannot be traced back to individual game-changing ships or devices, such as mine countermeasures.

COMMISSIONED PAPER 4

Transitioning Technology to Naval Ships

Norbert Doerry, Naval Sea Systems Command (June 18, 2010)

Transitioning technology from the academic and industrial research environment to installation on U.S. Navy ships is a complex process that intersects five domains: the science and technology community, resource sponsors, the acquisition and engineering community, industry, and the fleet. This paper presents both the current model and an alternative model for technology transition. The models reflect three drivers for inserting a new technology into a given system: filling a military capability gap, exploiting technology opportunities, and managing risk across a portfolio of systems. A discussion of how the different domains affect the processes is included. The paper continues with a discussion of technology transition challenges, provides technology transition examples, and offers recommendations to improve the process.

COMMISSIONED PAPER 5

Naval Ship Design and Construction: Topics for the R&D Community

Paul E. Sullivan, USEC, Inc. (June 10, 2010)

The U.S. naval shipbuilding establishment has produced the best, most technologically advanced, and most powerful navy in history. However, the price that the nation pays for naval superiority has caused erosion of the number of ships in the fleet to the point that there are chronically insufficient resources to fulfill the Navy's global commitment. The Chief of Naval Operations has stated the requirement for 313 to 324 battle-force ships. Yet the fleet hovers at about 280 ships, and this number is unlikely to increase significantly without substantial additional investment in new construction or significant service life extensions of ships in the inventory. The naval shipbuilding plans that could quickly bring ship numbers to required strength are unaffordable in the context of a constrained shipbuilding budget. Simply put, numbers count. Unless the overall cost of the fleet can be driven down dramatically without sacrificing military superiority, the U.S. Navy will remain short of resources to cover the need.

The biggest cost driver for naval shipbuilding is, in fact, mission requirements. Quality and high performance cost money. Battle-force ships will never be inexpensive. However, the shipbuilding community has the obligation to help the requirements community by instituting technology initiatives, process initiatives, and policy revisions that result in "game-changing" influence on the requirements–cost trade-off process. In addition, there are a myriad of issues driving shipbuilding costs that do not influence mission requirements, and the community could adapt them for all shipbuilding programs. This paper explores the needs for substantive improvement in shipbuilding costs as follows:

- Cultural changes in the approach to requirements, ship design, and ship construction that could reduce the overall cost of battle-force ships;
- Process changes and design tools that could substantively reduce the time needed for and the cost of designing and constructing naval ships; and
- Technology improvements that can simplify and reduce the cost of ship construction and life-cycle maintenance.

The 30-year shipbuilding plan sent to Congress with the FY 2011 budget requires a pace of 12 to 15 ships per year of all types. However, the Navy's shipbuilding and conversion budget for the past decade has provided only seven to nine ships per year. There is little prospect of the budget increasing in real terms, so the shipbuilding plan is likely unaffordable. The naval ship design and construction community must embrace many changes to give the Chief of Naval Operations options for building the battle-force ships required by the 30-year shipbuilding plan.

COMMISSIONED PAPER 6

Science and Technology Challenges and Potential Game-Changing Opportunities

Michael Triantafyllou, Massachusetts Institute of Technology (May 2010)

The future of naval engineering in the 21st century will be shaped by novel and emerging technologies. These technologies will provide unprecedented capabilities but will require radical rethinking of naval ship and vehicle design. This change is already in the works as engineering schools in major universities are hiring young faculty trained in new fields and developing novel technologies. This investment is expected to bring radical changes to mature fields, such as naval architecture and marine engineering; hence it is necessary to prepare the ground now to reap the benefits.

The paper is structured on the basis of these emerging technologies and the impact they are expected to have, providing discussion of their impact on naval ships and vessels and their capabilities. Traditional mechanical engineering departments and naval architecture and marine engineering schools are turning increasingly toward nanoengineering, novel power trains and synthetic fuels, and robotic devices and smart sensors to revitalize mature disciplines.

A discussion of the implications of the following emerging technologies and fields for naval ship design is given:

- Efficient power trains, especially of the hybrid type; efficient engines using alternative fuels, which are more sustainable and environmentally friendly; and fuel cells that use conventional fuels more efficiently;
- Progress in surface chemistry allowing the development of novel coatings to protect ship hulls and cargo holds, reduce deposits in pipelines, and reduce fluid drag;
- The all-electric ship, which has generated new methods for designing and operating ships with increased automation, reduced manning, and increased reliability;

- New sensor arrays, which will allow sensing of the self-generated flow and will create the capability for active flow manipulation and hence increased capabilities for maneuvering and efficient propulsion;
- Robotic developments that promise routine unmanned inspection and remote underwater intervention;
- Smart autonomous underwater vehicles (AUVs) that increase substantially the operational capability of ships and submarines. Naval ship and submarine design will be influenced significantly by the need to accommodate the storage and servicing as well as the launching and retrieval of AUVs in rough weather;
- New high-strength steels that improve hull protection against impact and fatigue, including operation in very cold climates; and
- Global ocean modeling and prediction that will allow effective routing and operation of vessels in rough seas with unprecedented detail.

The paper closes with an assessment of the shape of future naval designs and the capabilities they will offer.

COMMISSIONED PAPER 7

The Future for Naval Engineering

Millard S. Firebaugh, University of Maryland (September 2010)

In the future, a broad integrating outlook on the part of naval engineering leadership is imperative for success. Success will be recognized in the form of a U.S. Navy that maintains naval dominance at costs that are reliable and reasonable in the context of the many other challenges the nation faces. The U.S. Navy must nurture leadership in naval engineering by paying close attention to the selection of leaders and by providing for their education and experience. Broad knowledge and consideration of future trends across all naval engineering elements will be critically important in creating naval systems that can serve effectively and efficiently for many years.

The U.S. Navy is highly dependent on technology, faces much uncertainty as to the capabilities of the future threat, is entering a period of even more intense downward pressure on its budget, and must absorb new technologies from across the globe to maintain superiority. Therefore, naval engineering faces business, programmatic, and technological challenges. The Navy exists to deploy military force from the sea in the national interest. For the most part, the Navy carries out its mission in highly developed and specialized ships. The technologies concerning ships and the systems and equipment that operate in and from those ships are the province of naval engineering.

In this paper three themes are discussed: first, the importance of developing the individuals who are the future for naval engineering; second, the key business, programmatic, and technological challenges that will be important in future naval engineering developments; and third, areas of knowledge that naval engineering leaders need to master, beyond the usual content of formal engineering education.

As with most great enterprises, naval engineering for the U.S. Navy is fundamentally about people—their imagination, knowledge, skills, dedication, culture, work ethic, and vision for the future.

COMMISSIONED PAPER 8

Composites Road to the Fleet: A Collaborative Success Story

John P. Hackett, Northrop Grumman Shipbuilding (June 18, 2010)

This paper traces the history of Northrop Grumman Shipbuilding—Gulf Coast's (NGSB-GC's) quest to bring composite materials to naval shipbuilding and the fleet. It will show the initial NGSB-GC independent research and development activity in composites, eventually leading to teaming with the Navy on major composite projects. Numerous small projects became stepping stones that enabled larger projects to go forward. Examples of composite applications that made it to the fleet, as well as some that did not, will be addressed. One example of a success, the development of the advanced enclosed mast–sensor system mast concept [its design, manufacture, test articles, and installation on the USS *Arthur W. Radford* (DD 968) as a demonstration] and eventually its implementation on the LPD 17 class of ships, will be discussed. Another case study, the DDG 51 Flight IIA composite hangar, a technical success that did not make it to the fleet, will be addressed. The high-speed vessel demonstrated the use of composites for the forward one-third of its 290-foot-long hull with its complex shape. These large composite structure successes made the next step, of a composite superstructure with embedded antennas and low observability, an achievable goal. The DDG 1000 class, with a composite superstructure, will become the first class of large U.S. Navy ships so outfitted.

COMMISSIONED PAPER 9

Human Systems Integration (HSI)/Crew Design Process Development in the Zumwalt Destroyer Program: A Case Study in the Importance of Wide Collaboration

John Hagan, Bath Iron Works (June 8, 2010)

The paper reviews the Bath Iron Works–led human–systems integration (HSI)–crew design effort in the DDG 1000 program, or Zumwalt destroyer, which was charged with deriving a highly detailed crew design coincident with and traceable to the hardware and software designs. The following are of special interest in the paper:

- A description of HSI processes and tools developed or adapted for DDG 1000, along with lessons learned and recommendations;
- The critical importance of collaboration, both inside the design team (intrateam) and with multiple outside entities (interteam); and
- The importance of HSI as a component of the systems engineering effort (rather than treating HSI as a component of logistics or as a standalone activity).

Study Committee Biographical Information

Martha R. Grabowski, *Chair*, is the McDevitt Associate Chair in Information Systems, Professor and Chair of the Business Administration Department, and Director of the Information Systems Program, Le Moyne College; and Research Professor, Department of Industrial and Systems Engineering, Rensselaer Polytechnic Institute (RPI). She is a former Chair of the National Research Council's (NRC's) Marine Board and recently (2010) completed service as vice chair of the NRC Ocean Studies Board's Committee on the Review of the Tsunami Warning and Forecast System and Overview of the Nation's Tsunami Preparedness. She received a BS in nautical science from the U.S. Merchant Marine Academy and an MS in industrial engineering, an MBA in management and information systems, and a PhD in management and information systems from RPI. Her teaching, research, and consulting focus on human factors in systems design, the impact of technology in safety-critical systems; risk analysis and risk mitigation in large-scale systems; the role of human and organizational error in high-consequence settings; and financial cybersecurity in complex, heterogeneous data environments. A licensed former Second Mate and retired Lieutenant Commander in the U.S. Naval Reserve, Dr. Grabowski also chaired the NRC Committee Evaluating Shipboard Display of Automatic Identification Systems and the NRC Committee on Advances in Navigation and Piloting. She served as a member of NRC's Division of Behavioral and Social Sciences and Education Committee on Human–Systems Integration and is currently a member of the NRC Task Force on Marine Safety and Human Factors. She has served as a member of four other NRC committees. She is member of the American Bureau of Shipping. Dr. Grabowski is widely published in engineering, information systems, large-scale systems, human systems and safety science journals and publications. She was named a lifetime National Associate of the National Academies in 2003.

Alan J. Brown is Professor of Aerospace and Ocean Engineering and NAVSEA Professor of Ship Design at Virginia Polytechnic Institute and State University (Virginia Tech). Before joining the faculty at Virginia Tech, he was Professor of Naval Architecture and Marine Engineering at Massachusetts Institute of Technology (MIT) (1993–1997) and Associate Professor of Naval Construction and Engineering at MIT (1992–1993). He is a retired Captain of the U.S. Navy and a retired U.S. Navy Engineering Duty Officer. He held assignments in ship operations, maintenance, repair, salvage, oil spill response, design, construction, ship systems research and development, and marine engineering on U.S. Navy ships and fleet staff, in shipyards, in the Naval Sea Systems Command, and in the Office of the Chief of Naval Operations. He earned a PhD in marine engineering at MIT, a BS and an MS in naval architecture and mechanical engineering at MIT, and a BA from La Verne College. He has conducted research in naval ship design and construction process, tanker structural design, and naval ship structures for survivability. Dr. Brown is a Fellow of the Society of Naval Architects and Marine Engineers. He was the recipient of the American Society of Naval Engineers (ASNE) Jimmie Hamilton Award for Best Original Paper in 2008, the ASNE Solberg Award for Outstanding Achievement in Research Related to Naval Engineering in 2007, the 2007–2008 Dean's Certificate of Teaching Excellence, and the Dean's Award for Excellence in Service in 2008.

Charles N. Calvano is Professor Emeritus of Total Ship Systems, Systems Engineering, and Mechanical Engineering at the Naval Postgraduate School in Monterey, California. His research interests include total ship systems engineering—systems engineering methods applied to the ship design environment and design and construction process; Navy surface ship survivability; and the design and integration of Navy combatant ships. Professor Calvano began his career in 1963 as a seagoing officer and was assigned in 1970 to the Boston Naval Shipyard as a drydocking officer and ship superintendent. In 1989 he became director of ship design and of advanced concepts and technology at Naval Sea Systems Command and in 1991 moved to the Naval Postgraduate School. He developed and put into operation the Total Ship Systems Engineering Design Center. Professor Calvano is a Fellow of the Society of Naval Architects and Marine Engineers, a Fellow of the Royal Institution of Naval Architects (United Kingdom), a Life Member of the American Society of Naval Engineers, and a member of the Tau Beta Pi Engineering Honor Society and the International Council on Systems Engineering. He earned an MS in ocean engineering and naval engineering from MIT in 1970 and a BS in engineering from the U.S. Naval Academy in 1963. He is a Professional Engineer in the Commonwealth of Virginia.

Edward N. Comstock is an Engineering Fellow in Mechanical Engineering at Raytheon Integrated Defense Systems, where he serves as the Ship Community of Practice Lead. Before joining Raytheon in 2006 he worked for 31 years with the Naval Sea Systems Command (NAVSEA) and 6 years with the Electric Boat Division of General Dynamics and with the Marine Turbine and Gear Department of General Electric. In NAVSEA, he last served as the Director for Science and Technology and acted as the Executive Director of the Ship Design, Integration, and Engineering Directorate and previously held positions as Chief Naval Architect, Executive Director, Surface Ship Design and Systems Engineering Group, and as the Principal Assistant, Shipbuilding and Conversion, Navy Appropriations Sponsor for the Chief of Naval Operations. He is the President of the Society of Naval Architects and Marine Engineers (SNAME) and a Council Member of the American Society of Naval Engineers (ASNE). He has received numerous professional awards, including the Presidential Meritorious Rank Award, Superior and Meritorious Civilian Service Awards, SNAME David W. Taylor Medal, ASNE Jimmie Hamilton Award, National Society of Professional Engineers' Engineer of the Year Award, Association of Scientists and Engineers Silver Medal, and the University of Michigan Rosenblatt Alumni Award. He is a Fellow of SNAME. Mr. Comstock received an MSE in ship hydrodynamics in 1974 and a BSE in naval architecture and marine engineering in 1970, both from the University of Michigan.

Narain G. Hingorani (Member, National Academy of Engineering) is a consultant in Los Altos Hills, California. He worked for the Electric Power Research Institute from 1974 to 1994, where he was Vice President, Electrical Systems Division, from 1989 to 1994. From 1968 to 1974, he was with the Bonneville Power Administration. Dr. Hingorani's consulting practice is in the application of power electronics to transmission, distribution, industrial power, and marine power systems. He is a life fellow of Institute of Electrical and Electronics Engineers. He received an MS and a PhD from the University of Manchester and a BE from the University of Baroda, Vadodara, Gujarat, India.

Leonard Imas is Associate Professor of Ocean Engineering at the Stevens Institute of Technology. Before joining the faculty at Stevens Institute of Technology, he was a principal scientist in the Fluid Mechanical Systems Group at the Anteon Corporation and prior to that was a lead research scientist in the Deepwater Development Group at Chevron–Texaco Energy Company. His specialization is in the development and utilization of computational fluid mechanics and optimization methods in design analysis applications involving marine hydrodynamics and low-speed aerodynamics. His work in this area has focused on aero-hydrodynamics of high-performance racing yachts. Dr. Imas is also involved in research on the hydrodynamics and hydro-acoustics of underwater swimmers and hydromechanics of surface effect ships. He is a member of the American Institute of Aeronautics and Astronautics and the Society of Naval Architects and Marine Engineers. He received a PhD in hydrodynamics from MIT in 1998, an ME in aeronautical engineering from RPI in 1992, and a BS in aeronautical engineering from RPI in 1990.

John D. Lee is Professor in the Department of Industrial and Systems Engineering at the University of Wisconsin–Madison. Previously, Dr. Lee was a Professor of Industrial Engineering at the University of Iowa and Director of Human Factors Research at the National Advanced Driving Simulator. Before moving to the University of Iowa, he was a research scientist and deputy director at Battelle Human Factors Transportation Center. He has a background in engineering and psychology. He earned a PhD in mechanical engineering and an MS in industrial engineering from the University of Illinois at Urbana–Champaign in 1992 and 1989, respectively. He received a BS in mechanical engineering and a BA in psychology from Lehigh University in Bethlehem, Pennsylvania, in 1988 and 1987, respectively. Dr. Lee has 16 years of research and consulting experience aimed at matching human capabilities to the demands of technologically intensive systems. His research addresses human error and performance in a broad range of application domains, from process control and the maritime industry to driving.

Nancy G. Leveson (Member, National Academy of Engineering) is Professor in the Department of Aeronautics and Astronautics at MIT. She earned a PhD in computer science, an MS in operations research, and a BA in mathematics from the University of California, Los Angeles. Her research focuses on all aspects of system safety including design, operations, management, and social aspects. She works in many industries, including aerospace, transportation, chemical plants, medical devices, nuclear power, hospitals, and oil and gas production. She served on the National Aeronautics and Space Administration Aerospace Safety Advisory Panel and the Baker Panel investigating safety culture in the Texas City Oil Refinery explosion and has been involved in many accident investigations, including serving as an expert advisor to the Columbia Accident Investigation Board and the Presidential Oil Spill Commission (*Deepwater Horizon*).

Donald Liu (Member, National Academy of Engineering) is retired Executive Vice President and Chief Technology Officer for the American Bureau of Shipping. His research and interests have focused on finite element structural applications, ship structural dynamics, hull loading, structural stability, and probabilistic methods of structural analysis. He co-authored the recent Society of Naval Architects and Marine Engineers (SNAME) book on strength of ships and ocean structures. Dr. Liu is a Fellow of SNAME. He was the recipient of the U.S. Coast Guard Meritorious Public Service Award for his contributions to marine safety in 2002, the 2004 David W. Taylor Medal from SNAME, and the 2006 Gibbs Brothers Medal from the National Academy of Sciences for outstanding contributions in the fields of naval architecture and marine engineering. He served on the National Research Council Committee on the Oil Pollution Act of 1990 Implementation Review. Dr. Liu received a B.S. degree from the U.S. Merchant Marine Academy, B.S. and M.S. degrees in naval architecture and marine engineering from MIT, and a PhD in mechanical engineering from the University of Arizona.

Malcolm MacKinnon III (Member, National Academy of Engineering), Retired Admiral of the U.S. Navy and past Marine Board chair, is Managing Member, emeritus of MSCL LLC, a consulting firm that specializes in ship engineering. Admiral MacKinnon previously served in various executive and command positions with the Navy from 1955 until his retirement in 1990, including Deputy Commander of Ship Design and Engineering in the Naval Sea Systems Command (NAVSEA), Chief Engineer of the Navy, and Vice Commander, NAVSEA. He was Project Officer for the design and construction of SeaLabII, an underwater habitat, and directed the conceptual design efforts for the Trident Class nuclear submarines. He is active in the Society of Naval Architects and Marine Engineers and the American Society of Naval Engineers. Admiral MacKinnon received a BS in naval science from the U.S. Naval Academy and an MS in naval architecture and marine engineering from MIT. He served on the Marine Board Committee to Review the National Oceanic and Atmospheric Administration's Fleet Replacement and Modernization Plan and on the Committee on Marine Transportation of Heavy Oil, and he recently chaired the Committee on U.S. Marine Salvage Response Capability: A Workshop.

Michael W. Toner is a retired executive vice president of General Dynamics. He was responsible for the Marine Systems group, which includes Bath Iron Works, Electric Boat, NASSCO, and AMSEA from 2003 until his retirement in December 2008. He had been a vice president of General Dynamics since January 2000 and president of Electric Boat from January 2000 to October 2003. Mr. Toner joined Electric Boat in 1965 as a test engineer and held positions including manager of Reactor Services, manager of Trident ship's management, assistant general superintendent of the pipe shop, and director of facilities management. In 1990, he was appointed Electric Boat's director of operations and directed production, planning and support activities from the start of a submarine's construction to its delivery. He was promoted to vice president of operations two years later. In 1994, he was appointed vice president of delivery and was responsible for production, delivery, and support activities at Electric Boat's five facilities in Connecticut, New Jersey, New York, and Rhode Island. In 1995, he became vice president of innovation and was responsible for all engineering and design activity. In 1998, he became senior vice president of Electric Boat. Mr. Toner earned a bachelor's degree in nuclear science from the New York Maritime College in 1965, a master's degree in engineering from the University of Connecticut in 1970, and an executive-level master's degree in business administration from the University of New Haven in 1982. He also received an honorary doctor of letters degree from Maine Maritime Academy and State University of New York Maritime College.

Albert J. Tucker is a consultant to defense technology companies. From 1994 through 2002, he was the director of the Ship Hull, Mechanical, and Electrical Science and Technology Division at the U.S. Office of Naval Research (ONR), where he directed an integrated science and technology program for naval architecture and marine engineering and programs on ship and submarine stealth, structures, hydrodynamics, electrical technologies, and ship automation. From 1985 until 1988 and from 1994 until his retirement in 2002, he served in positions of increasing responsibility at ONR; from 1988 until 1991 he served as the Stealth Program Manager at the Defense Advanced Research Projects Agency, and from 1964 until 1985 he worked as a chief scientist and research physicist at the Naval Surface Warfare Center. Dr. Tucker is a member of the Virginia Tech Advisory Board and a member of the Institute of Electrical and Electronics Engineers. He received a PhD in mechanical engineering from the Catholic University of America in 1973, an MS in engineering mechanics from Penn State University in 1964, and a BS in physics from the University of Massachusetts in 1962. Dr. Tucker has coordinated international technical exchanges in naval engineering, has established a university research consortium, and is a member of Sigma Xi.

Vincent Wilczynski is Deputy Dean, School of Engineering and Applied Science, Yale University. Until 2010, he was Head of Engineering at the U.S. Coast Guard Academy. Captain Wilczynski served as the National Director of the Foundation for Inspiration and Recognition of Science and Technology (FIRST) Robotics Competition. Before beginning his teaching career, he served as a shipboard engineer and as a staff engineer and staff naval architect at the U.S. Coast Guard Marine Safety Center. He earned a PhD in mechanical engineering at Catholic University in 1992; MS degrees in mechanical engineering and in naval architecture and marine engineering from MIT in 1987; and a BS in naval architecture and mechanical engineering from the U.S. Coast Guard Academy in 1983. He serves as the Vice President of the Center for Public Awareness for the American Society of Mechanical Engineers (ASME) and on the Executive Advisory Board of the FIRST Robotics Foundation, and he previously served as a national officer of the American Society for Engineering Education, as an evaluator for the New England Association of Schools and Colleges, and as a member of the State of Connecticut Department of Higher Education Board of Governor's Advisory Committee on Accreditation. Captain Wilczynski was named the 2001 Baccalaureate Colleges Professor of the Year by the Carnegie Foundation for the Advancement of Teaching. He received the 2005 ASME Church Medal for outstanding contributions in mechanical engineering education. He is a Fellow with the American Council on Education and a Fellow of ASME.

Cindy Williams is a Principal Research Scientist in the Security Studies Program of MIT. Her work at MIT includes an examination of the processes by which the U.S. government plans and budgets for national security and international affairs and an examination of the transition to all-volunteer forces in the militaries of several European countries. Formerly she was an Assistant Director of the Congressional Budget Office, where she led the National Security Division in studies of budgetary and policy choices related to defense and international security. Dr. Williams has served as a director and in other capacities at the Mitre Corporation in Bedford, Massachusetts; as a member of the Senior Executive Service in the Office of the Secretary of Defense at the Pentagon; and as a mathematician at Rand in Santa Monica, California. Her areas of specialization include the U.S. national security budget, military personnel policy, command and control of military forces, and conventional air and ground forces. Dr. Williams holds a PhD in mathematics from the University of California, Irvine. She is an elected fellow of the National Academy of Public Administration and a member of the Naval Studies Board, the Council on Foreign Relations, and the International Institute for Strategic Studies. She serves on the advisory board of Women in International Security and on the editorial board of *International Security*.

Ronald W. Yeung is Distinguished Professor of Hydromechanics and Ocean Engineering at the University of California, Berkeley. He was a visiting professor at the Center of Excellence for Ships and Ocean Structures, Norwegian University of Science and Technology, Trondheim in 2007; Humboldt Professor at the Institut für Schifftechnischen, Gerhard Mercator University of Duisburg, Germany in 1998; visiting professor at the Research Institute of Applied Mechanics, Kyushu University, Japan in 1998; and Humboldt Professor at the Institut für Schiffbau, University of Hamburg, West Germany in 1988. From 1970 to 1971, he was a naval architect in the Advanced Marine Technology Division of Litton Ship Systems in Culver City, California. From 1974 to 1982, he was Assistant and then Associate Professor of Naval Architecture at the Massachusetts Institute of Technology. He was the recipient of the Brazilian Society of Marine Engineers 2008 International Researcher Award; the Bill Zimmie Award from the University of Michigan, Ann Arbor, in 2006; and the Kenneth Davidson Gold Medal from the Society of Naval Architects and Marine Engineers (SNAME) in 2004. He was elected Fellow of SNAME in 1998 and was appointed the 2002–2003 Georg Weinblum Lecturer by the Deutsche Schiffbaugesellschaft and the Naval Studies Board of the National Research Council. In 2010, he received an Honorary Professorship from Harbin Engineering University, China. Dr. Yeung received his PhD from the University of California, Berkeley, in 1973.

Solomon C. Yim is Professor in the Department of Civil and Construction Engineering at Oregon State University (OSU). Past positions include Structural Engineering Program Coordinator, OSU; Researcher in Civil Engineering, University of California, Berkeley; Researcher at Exxon Production Research Company; and consultant to the Naval Facilities Center. He specializes in the dynamics of structures in the marine environment. He earned a PhD in civil engineering from the University of California, Berkeley, in 1983; an MA in mathematics in 1981 and an MS in civil engineering in 1981 from the University of California, Berkeley; and a BS in civil engineering in 1976 from Rice University. Dr. Yim is a member of the American Society of Civil Engineers and the U.S. Association for Computational Mechanics and is a Fellow of the American Society of Mechanical Engineers. He has served as a member of the Marine Board's Ship Structures Design Work Group and its Ship Structures Committee and on the organizing committee for the Symposium and Workshop on the Prevention of Fracture in Ship Structures. He has served on numerous other organizing committees, technical program committees, and editorial boards. He received the U.S. Office of Naval Research Young Investigator Award in 1988–1991, was the U.S. Navy–American Society of Engineering Education Senior Faculty Research Fellow in 1993, and was Royal Norwegian Research Council Senior Visiting Research Scientist in 1994.

Dick K. P. Yue is Professor of Mechanical and Ocean Engineering and Director of International Programs at the Massachusetts Institute of Technology (MIT). His career has included research on computational hydrodynamics, research and teaching in marine fluid mechanics, and the application of biomimetic principles to marine design. He is the former Associate Dean of Engineering and the developer of unique education programs and instructional methods and tools. Dr. Yue earned a ScD/PhD, an MS, and a BS in civil engineering from MIT in 1980, 1976, and 1974, respectively. He is the recipient of numerous honors and awards, including the MIT Class of 1960 Innovation in Education Award and Fellowship (2006–2008), the Japanese Government Foreign Specialist Research Award (1987), the Henry L. Doherty Chair Professorship (1984–1986), and the Arthur T. Ippen Fellow (1976). Dr. Yue is a life member of the American Physical Society and of the Society of Naval Architects and Marine Engineers.