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Assessing the Benefits and Costs of a Science Submarine

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Preface

After the end of the Cold War, the U.S. Navy made SSN 637-class nuclear attack submarines available to the scientific community to conduct scientific research underneath the Arctic sea ice caps. Sponsored by the Navy and civilian science agencies, these missions provided a wealth of important scientific data. However, this class of submarine is now retiring from the Navy's active fleet, and it has been proposed that one of these vessels be converted into a dedicated research platform.

The National Science Foundation asked RAND's Science and Technology Policy Institute to assess the costs and benefits of operating an SSN 637-class nuclear submarine for unclassified scientific research throughout the world's oceans. This draft presents results of this assessment.

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Summary

Sponsored by the Navy and civilian science agencies, the SCICEX (Scientific Ice Exercise) missions conducted between 1993 and 1999 used nuclear attack submarines as platforms for gathering scientific data. The importance of these data were magnified by the fact that he Arctic Ocean has been the subject of less scientific study than any of Earth's other oceans, even though it contains vital economic resources and is a critical factor in and potential harbinger of global climate change.

The SCICEX cruises confirmed the unique capabilities of nuclear submarines as platforms for scientific research. Their ability to move quickly and easily beneath the ice caps in any weather and any season enables an extraordinary range of data-collection activities. Moreover, the U.S. Navy's long, successful history of conducting Arctic research from nuclear submarines has shown the feasibility of these submarines as scientific research platforms.

However, the last SCICEX mission ended in November 2000, and the SSN 637-class submarines are now retiring from the Navy's active fleet. To preserve the possibility of using this unique research platform, it has been proposed that one of these vessels be converted into a dedicated science submarine, conducting unclassified scientific research throughout the world's oceans.

To inform its deliberations on this proposal, the National Science Foundation (NSF) asked RAND to assess the costs and benefits of a dedicated science submarine. This study addresses two core questions:

- What are the research benefits of using a converted SSN 637-class nuclear attack submarine solely for civilian scientific research?
- What are the costs of operating, maintaining, and manning such a submarine?

Research Approach

To address these questions, the RAND study team assesses the benefits and costs of a science submarine. As a concrete example, we consider the conversion of SSN 686, the *L. Mendel Rivers,* the last, recently retired SSN 637 hull, into a scientific platform. We envision the *Rivers* operating for seven years, conducting a variety of scientific observations on three, 40-day cruises each

year. Each cruise would follow a course determined by scientific requirements and carry 15 scientific researchers on board.

We estimate the benefits of such a science submarine with qualitative assessments of its potential contributions to high-priority national research goals as identified by the scientific community. These goals fall in the topic areas of Geologic and Geophysical Exploration in the Arctic Basin, Arctic Climate Change, the Dynamics of Bering Sea Ecosystems, and general Oceanographic Studies in the Ice-Free Oceans. We focus on the unique contributions of a science submarine, that is, the benefits gained by adding a submarine to the existing portfolio of research platforms for the Arctic. These platforms include surface ships, icebreakers, satellites, autonomous underwater vehicles (AUVs), ice camps, airplanes, remote buoys, and instrumentation for acoustic propagation measurements. We first identify the unique measurements that could be provided by a submarine. We then place these measurements in a framework that relates measurements to the high-priority research goals they address. We choose this approach as a means to address the notoriously hard problem of estimating the benefits from scientific research. This approach to benefits assessment is consistent with NSF's common assessment of large research facilities, but addresses the exceptionally interdisciplinary quality of submarine data.

We then estimate the costs to convert, maintain, and operate a dedicated science submarine by starting with extensive Navy data on the comparable costs of a military submarine. We then develop a variety of cost scenarios, making different assumptions about how these costs might be reduced for scientific operations.

Scientific Benefits

We find that the most important contribution of a dedicated science submarine would be its ability to collect survey data in ice-covered seas. With its ability to navigate freely during all seasons and in all weather, a submarine is unmatched in its capability to collect large amounts of bathymetric or hydrographic data over the Arctic Basin, especially in the winter. A submarine also has unique capabilities to collect controlled seismic refraction and reflection surveys. Such data directly support the geological and geophysical exploration of the Arctic Ocean Basin.

A dedicated science submarine could also make unique contributions to understanding climate change in the Arctic and its relationship to global climate change. For climate change research, the most important feature of the submarine is the capability to collect data over broad areas of the Arctic Basin at all times of year. Of particular importance are hydrographic measurements in the upper ocean (temperature/salinity profiles), detailed mapping of ice draft and structure, and high-resolution bathymetric surveys.

The science submarine could also uniquely contribute to understanding Bering Sea ecosystems. The submarine has a unique capability to make hydrographic and ice draft measurements under the ice in those regions of the Bering Sea where the water is sufficiently deep for safe operations and can also make unique contributions by monitoring biological features, such as water sampling from specific oceanographic features and mapping fish and zooplankton populations using the submarine's sonar systems, in ice-covered seas.

In the ice-free oceans, the submarine has fewer unique capabilities relative to surface ships, satellites, and drifting buoys. Without the limitations of an ice cover, ships have greater navigational capabilities, satellites can image a range of ocean properties over vast areas, and buoys can drift great distances. Under these circumstances, the submarine's primary strength centers on data gathering in remote regions, rough seas, and bad weather.

Our analysis focuses on the benefits of a dedicated science submarine in relation to the proven, current capabilities of other research platforms. We note, however, that autonomous underwater vehicles (AUV) technology is improving rapidly and could possibly equal or surpass many of the submarine's unique measurement capabilities over the course of roughly a decade.

Costs

The total cost of operating and maintaining the *L. Mendel Rivers* as a dedicated science submarine could range from roughly $200 million to $300 million over an expected seven years of operation. Approximately $95 million to $125 million would be required for depot overhaul and science conversion, $20 million to $38 million for depot maintenance, $37 million to $55 million for operations including the cost of a Navy crew and consumables, and approximately $60 million for science support. The wide variation of potential costs is largely due to varying assumptions about whether the submarine could be overhauled and maintained at public or private shipyards, the allocation of overhead, and cost sharing between NSF and the Navy. These issues would likely be resolved and the cost made clearer if and when the government begins serious planning for a dedicated science submarine. The average annual cost of the submarine would range from $30 million to $40 million per year. By comparison, current NSF funding for Arctic research, logistics, and facilities support totaled approximately $70 million in fiscal year (FY) 2000.

The cost of the submarine is unevenly distributed over time. The initial overhaul and science conversion of the existing vessel constitutes more than a third of the total lifetime costs of the science submarine. Thus in any scenario, the majority of spending would occur in the first years of the program, and hence there is little flexibility to reduce costs by focusing the dedicated science submarine on a few high-priority missions.

Assessment

A dedicated science submarine could make unique and important contributions to the priority research areas of Geologic and Geophysical Exploration of the Arctic Basin and Arctic Climate Change. It could make unique, important, though relatively lesser contributions to the priority research areas of the Bering Sea Ecosystem and General Oceanographic Studies in the Ice-Free Oceans. Maintaining and operating a science submarine could cost $200 million to $300 million over seven years of operations. Many uncertainties remain over the extent of these benefits and costs. For instance, the submarine could have nonscientific benefits not considered in this study; or technological advances could produce autonomous underwater vehicles that in a decade or more could obtain some of the measurements currently available only from a dedicated science submarine. Nonetheless, this report lays a foundation for decisionmaking on the deployment of such a research platform. Specifically we identify the priority research areas that would benefit most from the unique capabilities of a dedicated science submarine. Policymakers can assess the importance of these benefits in light of the costs we have identified.

Acknowledgements

This study benefited from the invaluable help of a great many individuals. Our advisory committee — Robert Anderson, Jack Bash, Bob Brown, Dale Chayes, Bernie Coakley, Dennis Conlon, Don Heinrichs, Edward F. McGinley, Peter McRoy, Barbara Moore, Drew Rothrock, Ray Sambrotto, James Swift, Frank Tesoriero, Barrie Walden — gave generously of their time and expertise in helping us frame and vet the study. Tom Pyle of the National Science Foundation and George Newton of the Arctic Research Commission were always available for thoughtful comments and advice throughout the course of our work. The Naval Sea Systems Command; Naval Center for Cost Analysis (NCCA); the Submarine Maintenance Engineering, Planning and Procurement (SUBMEPP) activity; and Electric Boat Corporation all provided information critical to our cost analysis. Douglas Brubaker, Norm Cherkis, Tom Crew, John Farrell, Peter Mikhalevsky, and Michael Maxall provided helpful insights on oceanographic research. James Bellingham offered helpful information about autonomous underwater vehicles. Gerald Schatz advised us on relevant issues of maritime law. Robert Anderson and Jeff Gossett of the Arctic Submarine Laboratory offered helpful input and comments, as did Gary Brass of the Arctic Research Commission. In their roles as RAND consultants, Mal McKinnon and Denis Rushworth contributed much to our analysis of the costs and capabilities of a dedicated science submarine. We also benefited greatly from the assistance of our RAND colleagues John Birkler, Bruce Don, and Steve Rattien. Finally, the meticulous comments of our reviewers, Jim Bartis and John Schank, greatly improved this document.

Chapter 1. Introduction

During the 1990s, the U.S. Navy made SSN 637-class nuclear attack submarines available to the scientific community to gather oceanographic data on dedicated cruises underneath the Arctic sea ice. Sponsored by the Navy and civilian science agencies, the SCICEX (Scientific Ice Exercise) missions provided a wealth of important scientific data. However, the SSN 637-class submarines are now retiring from the Navy's active fleet, and the last SCICEX mission ended in November 2000. It has been proposed that one of these vessels be converted into a dedicated scientific research platform for unclassified scientific research throughout the world's oceans.

To inform its deliberations on the proposal, the National Science Foundation (NSF) asked RAND to assess the costs and benefits of a dedicated science submarine. This study addresses two core questions:

- What are the research benefits of dedicating a SSN 637-class nuclear submarine exclusively to civilian science research?
- What are the costs of operating, maintaining, and manning such a submarine?

Rationale for a Dedicated Science Submarine

Due to the Arctic's inaccessibility, far less oceanographic data are available on the Arctic Ocean than on the Earth's other oceans. But the Arctic region is at least as important. It contains critical fisheries, minerals, and oil, gas, and coal deposits. The polar regions are also expected to be harbingers of any changes in the Earth's climate, which should appear more strongly and clearly than in the Earth's temperate regions.

It has long been recognized that nuclear-powered submarines have capabilities that might make them a valuable platform for scientific research. In the Arctic Ocean, nuclear submarines can move quickly, quietly, and easily under the ice to almost any location, collecting a wide variety of data sets in any season. In the Arctic and the open oceans, a submarine can operate in almost any weather conditions and can move quickly to station, facilitating measurements in remote regions.

The Navy has a long, successful history of research from nuclear submarines in the Arctic that has demonstrated the feasibility of submarine-based research and the novel qualities of submarine datasets. The six SCICEX cruises conducted from 1993–1999 used Navy submarines with only minor modifications, with civilian scientists on board for scientific missions of several weeks' duration. These cruises collected a broad range of data on the bathymetry, hydrography, ocean chemistry, and ice thickness throughout the Arctic Basin. These data contributed to a variety of important sciences. For instance, it contributed to the recent observation that the Arctic ice cover has thinned significantly over the last several decades.[1]

This potential has been recognized in a variety of official studies. The 1996 UNOLS report *A Nuclear-Powered Submarine Dedicated to Earth, Ocean, and Atmospheric Research*,[2] found that the principal advantage of using a nuclear-powered submarine for research involved:

- "Working under the ice in high latitudes, where a submarine can move more quickly and, if the water is deep enough, more easily than a surface research ship on the open ocean."
- "Working in very bad weather, where a surface ship cannot operate efficiently, or at all."

In a National Research Council report, a scientific panel considered the need for a new icebreaker dedicated to scientific research in the Arctic. As part of its analysis, the panel compared the research capabilities for the proposed icebreaker against a nuclear-powered submarine, as demonstrated by the initial SCICEX cruises. They concluded:

> The ability of a submarine to cruise beneath the ice at high speed independent of surface weather or ice conditions makes possible scientific investigations that require large amounts of under-ice areal coverage. In fact, submarine based capabilities are strongly preferred for most tasks comprising the proposed marine geology and geophysics research in the Arctic and would also be useful for other studies.[3]

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[1]Rothrock, D.A., Y. Yu, & G.A. Maykut, 1999. "Thinning of the arctic sea-ice cover," *Geophys. Res. Lett.*, 26(23), 3469–72.
[2]In this context, atmospheric research involves measurements of ocean processes and properties that influence the state of the atmosphere.
[3]*Arctic Ocean Research and Supporting Facilities: National Needs and Goals*, National Research Council, National Academy Press, Washington D.C., 83 pages, 1995; p. 71.

Examining the Benefits and Costs

With the ending of the SCICEX program, the Navy and NSF must decide whether and how to support a dedicated science submarine. In order to inform such a choice, decisionmakers need a systematic assessment of the benefits and costs of a dedicated science submarine. The submarine's potential contribution must be weighed against a backdrop of existing, broad-ranging strategies for scientific research on the Arctic region (e.g., other data collection efforts, laboratory measurements, and modeling).

In this study, we examine the benefits and costs of such a dedicated science submarine. As a concrete example, we consider the conversion of SSN 686, the *L. Mendel Rivers,* the last, recently retired SSN 637 hull, to such a science platform. We envision the *Rivers* operating for seven years, conducting a variety of scientific observations on three, 40-day cruises each year. Each cruise would follow a course determined by scientific requirements and carry 15 scientific researchers onboard.

We estimate the benefits of such a science submarine by qualitatively estimating its potential contributions to high-priority national research goals as identified by the scientific community. These goals fall in the topic areas of Geologic and Geophysical Exploration in the Arctic Basin, Arctic Climate Change, the Dynamics of Bering Sea Ecosystems, and general Oceanographic Studies in the Ice-Free Oceans. We focus on the unique contributions of a science submarine, that is, the benefits gained by adding a submarine to the existing portfolio of research platforms for the Arctic. These platforms include icebreakers, ice camps; aircraft; satellites; and remote, fixed buoys. We first identify the unique measurements that could be provided by a submarine. We then place these measurements in a framework that relates measurements to the high-priority research goals they address. We choose this approach as a means to address the notoriously hard problem of estimating the benefits from scientific research. This approach to benefits assessment is consistent with NSF's common assessment of large research facilities, but addresses the exceptionally interdisciplinary quality of submarine data.

We next estimate the costs to convert, maintain, and operate a science submarine by starting with extensive Navy data on the related costs of a military submarine. We then develop a variety of cost scenarios, making different assumptions about how these costs might be reduced for scientific operations.

We find that a dedicated science submarine could make unique and important contributions to the priority research areas of Geologic and Geophysical Exploration of the Arctic Basin and Arctic Climate Change; and lesser but important contributions to the priority research areas of the Bering Sea Ecosystem, and general Oceanographic Studies in the Ice-Free Oceans. The submarine's most important contributions are due to its ability to navigate freely in ice-covered oceans. We also find that the operations and maintenance costs of a dedicated science submarine would be significant compared to current civilian research budgets. Existing research facilities could approximate, or improve on, many of the measurements that could potentially be made by the submarine. An analysis of technological trends in oceanography suggests that a dedicated science submarine's capabilities would likely have the largest impact during the *Rivers'* remaining lifetime of seven years, after which alternative facilities may become available to perform similar tasks at potentially lower costs.

Organization of the Report

Chapter 2 discusses the unique measurement capabilities of a science submarine. Chapter 3 examines how these measurement capabilities could contribute to high-priority national research goals. Chapter 4 presents our assessment of the costs of a dedicated science submarine. Chapter 5 summarizes our conclusions. Additional details of the analysis are provided in the six appendices.

Chapter 2. The Benefits of a Science Submarine

The potential benefits of a science submarine have been discussed since the early 1990s. At the end of the Cold War, as the sensitivity of Arctic research diminished, the Chairman of the Fleet Improvement Committee for the University-National Oceanographic Laboratory System (UNOLS) wrote a "Dear Colleague" letter to the scientific community, stating:

> The current window of opportunity for uses of nuclear submarines has been opened by a number of developments. Perhaps the most significant is the reduced military threat posed by the former Soviet Union. This event raises the possibility of reducing the size of the fleet and/or defining new missions of military and social relevance for nuclear submarines. In addition, it seems likely that certain security measures associated with nuclear submarine operation, data acquisition, and data accessibility might be relaxed so that data collected by a nuclear submarine could be analyzed by scientists and published in the open literature.[1]

This letter was preceded by a number of general publications advocating unclassified research missions for nuclear-powered submarines. At the time, it was noted that the Navy planned to decommission many of its SSN 637-class submarines before the end of their 30-year life. From a scientific perspective, these were the most attractive platforms because they could surface through the Arctic ice without damage. And unlike diesel-electric submarines, they could operate below the surface for many weeks.

Building on the long and successful history of classified submarine research in the Arctic, analysis focused on the submarine's unique capability to collect data in ice-covered seas, a capability that was difficult to match using current unclassified facilities. With this motivation, through the 1990s, the scientific community identified a range of research missions for a nuclear-powered submarine. These were articulated in four consensus reports and benchmarked during the six SCICEX cruises.

In this study, we draw on this extensive analysis to build a systematic, qualitative framework that allows the benefits of a dedicated science submarine to be weighed against the costs. First, we identify the capabilities of a submarine to collect data in the polar regions and the open oceans. Then, we

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[1] "Dear Colleague" Letter, included as a preface to the report *Scientific Opportunities Offered by a Nuclear Submarine (SOONS); A Report from the UNOLS Fleet Improvement Committee,* 7 pages, January 1992.

compare these capabilities to other platforms. In the next chapter, we estimate the importance of the research enabled by the submarine's capabilities in the context of the priority research objectives. From this analysis we identify the research areas where a scientific submarine would have the largest impact.

Approach to the Benefits Assessment

It is notoriously difficult to measure the benefits of scientific research. Often, research provides benefits that are difficult to quantify, such as improved intellectual understanding on a specific topic without immediate practical implications, and may not become apparent for many years. Mindful of these difficulties, we have undertaken a qualitative assessment of the science submarine's benefits for comparison with quantitative estimates of the submarine's costs.

Conceptual Framework

In this chapter, we focus on unique submarine research capabilities that cannot be replicated by other platforms. In the next chapter, we assess the capabilities using a hierarchy that links high-level scientific objectives to specific research activities. Government and industry commonly use hierarchies of goals to facilitate *ex-ante* decisions for scientific programs. In particular, this is the implicit methodology used by NSF to evaluate investments in new research facilities such as oceanographic research vessels, advanced telescopes, supercomputing research centers, and other large capital expenditures that provide unique capabilities to investigate important scientific problems. For instance, as stated in 1999–2003 facilities plan for the Geosciences Directorate (GEO):

> It is crucial to maintain and strengthen links between facilities and the research they support. The GEO facility capabilities must be driven by research needs. Facility selection, operation, and management procedures must allow continuous evolution of capability to match community needs. This "matching" of facility capabilities to research needs must occur at every level—from the interaction of individual investigators with facility providers, to maintaining clear links between the goals enumerated here with those in the GEO Science Plan, FY 1998–2002.[2]

[2]GEO Facilities Plan: 1999–2003, National Science Foundation Report 99-139, 37 pages, 1999; p. 6.

That is, the need for a new platform should be judged in terms of its contribution to priority research missions. We develop the hierarchy of goals in reference to four broad research areas, defined from the recommendations of past proposals for a science submarine. The research areas are described below with a more-detailed discussion in Appendix C.

Arctic Climate Change and Its Relationship to Global Climate Change. Satellite and submarine observations provide growing evidence of climate change in the Arctic. A key challenge is to understand the origin of these changes and to identify the links to global climate change processes. For example, the Arctic may provide indicators of global climate change that are difficult to identify in temperate regions. Alternatively, changes in the Arctic climate may influence the climate in other regions.

Geologic and Geophysical Exploration in the Arctic Basin. Geologic and geophysical exploration of the ocean basins has contributed to a range of practical and scientific discoveries, including plate tectonics, mineral and fossil fuel deposits, and even the origin of life on Earth. While there is great interest in extending this research to the Arctic Basin, past efforts have been limited by ice conditions that preclude all but specialized oceanographic expeditions.

Understanding the Dynamics of the Bering Sea Ecosystem. The Bering Sea supports a vast range of marine life that is vital to the broader Arctic ecosystem, to the livelihoods of the local population, and is important to the U.S. economy. More than 50 percent of all U.S. commercial fish are caught in this ecosystem. However, biological studies indicate this ecosystem is under severe stress, reflected in reduced diversity and size of fish and shellfish populations. For these reasons the U.S. Arctic Research Commission has identified research in this area one of its priorities for basic Arctic research. Understanding and addressing these problems will require comprehensive monitoring and analysis.

Oceanographic Studies in the Ice-Free Oceans. Research in the ice-free oceans is focused in three general areas: elucidating the connection between ocean processes and global climate, understanding the health and sustainability of critical ocean ecosystems, and characterizing the geology and geophysics of the marine basins.

Within these research areas, we analyze the submarine's capability to make a range of measurements. We compare its performance to that of other platforms in identifying unique submarine capabilities for data collection. For our analysis, these capabilities are the submarine's most important characteristics. Then, we identify the impact of a submarine by correlating current research needs, in the above topic areas, with the unique submarine capabilities. Where there is a correlation, we conclude that a scientific submarine would make a unique contribution to a priority research topic.

Our approach provides decisionmakers with a systematic structure to evaluate the contributions of a research submarine, subject to their own judgments of scientific benefits. Given the challenges for an *ex-ante* assessment of scientific benefits, we will not provide decisionmakers with a quantitative estimate of the benefits which could be compared to the costs for of a scientific submarine. Such an analysis depends on subjective weightings of alternative goals within scientific agendas. Different decisionmakers and stakeholders will hold different subjective weightings, and a full elaboration is beyond the scope of this study.

The benefit and cost comparison in this study is designed to address the question of whether or not the U.S. government should add a dedicated science submarine to its suite of existing research platforms in the Arctic. We do not address the question of whether the United States could more effectively achieve its goals by substituting a science submarine for existing platforms. We believe the former question more accurately addresses the issue presently facing the National Science Foundation. NSF has already made significant investments in the hardware and perhaps more importantly, the intellectual capital, associated with research programs designed around existing platforms. In addition, these research platforms are not readily substitutable. We will argue that a science submarine has unique capabilities compared to platforms such as icebreakers, ice camps, aircraft, and autonomous underwater vehicles. That is, there are data that would become available with a dedicated science submarine that would not reasonably be obtainable without such a platform. However, other platforms also have unique capabilities compared to the submarine's. Thus, this study does not address the issue of whether priority research areas could be better addressed by gathering some new data while foregoing current data collection activities. Rather, we examine the benefits and costs of augmenting these current activities, that is, we lay out the scientific contributions that would only become available by deploying such a submarine and the incremental costs of doing so.

Assumptions of the Benefits Analysis

Our analysis of the benefits is bounded by several important assumptions. First, we focus only on the civilian scientific benefits of a dedicated submarine. We recognize that a scientific submarine could also benefit the Navy by providing an additional platform for training, or collecting oceanographic data to improve submarine systems, tactics, and operations. At the same time, there could also be benefits to the U.S. government associated with the conversion of SSN 686. Extending the life and applications for the hull might be one strategy to maximize the value of the original investment in the submarine and its systems. The bathymetric surveys collected by a dedicated scientific submarine could provide the United States and other nations increased ability to claim sovereignty over continental shelved under the provisions of the Law of the Sea Treaty. Finally, a scientific submarine could foster public awareness of science. While these benefits are potentially important, they fall outside of the scope of our analysis, which focuses on decisionmaking within the civilian research community. For these reasons, our analysis provides a lower bound on the benefits that could be augmented by a broader analysis to support decisionmaking at an interagency level.

Second, we focus the benefits of a *dedicated* science submarine. While we recognize that alternative mission scenarios may be of interest to civilian decisionmakers (e.g., shared civilian-military use of SSN 686, continued SCICEX cruises, etc.), these were not within the charter of our study as defined by NSF. Thus our analysis focuses on the scenario yielding the maximum scientific benefit from a submarine, at presumably the maximum costs.

Finally, our analysis of the scientific benefit focuses on research problems that have been identified and are viewed as addressable, given current or anticipated research facilities. Our benefits analysis does not examine the impact of entirely new or unforeseen capabilities that have not been demonstrated. While we recognize that substantial scientific benefits often derive from unexpected breakthroughs in measurement capabilities, we believe that ours is the most reasonable approach for two reasons. First, civilian scientific agencies are traditionally risk-averse when considering investments in expensive scientific facilities, focusing on the most likely benefits. Second, the potential for a scientific submarine has been analyzed extensively by the research community, reducing the likelihood of unidentified capabilities in the near term. (This observation points to the importance of the SCICEX program as an effective demonstration of the potential submarine contributions.) While an analysis that considered breakthrough or "out-of-the-box" capabilities might increase the benefits from a dedicated submarine, our focus of unforeseen capabilities does not bias the assessment, since it is also possible that alternatives, such as autonomous underwater vehicles (AUVs) will experience greater-than-expected advances during the time period considered by this study.

The Capabilities of a Science Submarine

What are a submarine's unique measurement and analytic capabilities? In essence we are asking "If a submarine were available, what types of data would it provide, and how would these compare to information that might be available from other platforms?" While this assessment resembles a straightforward technical assessment that NSF might carry out as part of the peer review process for a scientific submarine program, there are a number of challenges given the breadth of the potential research applications. For example:

- Scientific data are characterized by a wide range of attributes, tailored to specific research problems (e.g., spatial coverage, precision, time resolution). In this setting, there is a need for well-defined criteria to assess the "uniqueness" of submarine data and capabilities.

- Different research platforms are designed to meet different operational goals and requirements. To avoid "apples vs. oranges" comparisons, there is a need to compare a submarine against a wide range of research facilities that collect comparable data. That is, the analysis will not focus on the capability of a single platform to replicate the data that might be collected by a submarine.

- The relative capabilities of research platforms are changing because of technological innovation. In particular, increases in AUV capabilities may decrease the extent of currently unique submarine capabilities over the course of the decade. While technological change could also increase the submarine capabilities through its impact on sensors, engineering systems, and collection schemes, the rate of improvement may be much faster for the AUVs.

Kinds of Data Collection Enabled by a Nuclear Submarine

With these caveats, we consider the data-gathering capabilities of a science submarine. For this analysis we focus on nine types of measurements that were demonstrated or proposed for the SCICEX program. These are all measurement areas where the submarine may have significant capabilities compared with other platforms because of the submarine's unique combination of all-weather and season access, speed, stability, and quietness. We do not include measurements for which a submarine clearly has limited comparative capability, such as setting of moorings, bottom coring, and bottom dredging. The measurements we consider are:

- Bathymetry and bottom profiling
- Water sampling for chemistry and microbiology
- Temperature/salinity profiles
- Gravity and magnetic surveys
- Seismic refraction and reflection profiles
- Biological monitoring via sonar
- Ice draft, structure, and detailed mapping
- Measurements of current
- Optical properties of water; ambient light levels
- Sound velocity profile.

We express the measurements in general terms (e.g., water sampling) to capture the broadest applications for a research submarine. In the following section, we summarize a submarine's capability to carry out each of these tasks:

Bathymetry and Bottom Profiling

A specialized sonar system has been designed and tested on SSN 637-class submarines for high-resolution bathymetric mapping and shallow acoustic reflection profiling from the ocean bottom. Known as the Seafloor Characterization and Mapping Pod (SCAMP), it consists of hydrodynamic housing, mounted on the submarine keel, with a SeaMARC type side-scan sonar and a Bathy-2000P FM modulated sub-bottom profiler. With dedicated cruising, the SCAMP system can collect approximately 9,500 km^2/day of high-resolution bathymetric maps (see Figure 2.1). The sub-bottom profiler has a resolution of approximately 10 cm, and it can detail structures to at least 100 m depth (see Figure 2.2). The SCAMP system has collected data for a range of scientific problems under the SCICEX cruises. This includes detailed mapping of the Gakkel Spreading Ridge, surveys for potential ocean drilling sites, large scale surveys of prominent topographic features in the Arctic Basin, mapping the extent of glacial features on the sea floor, and preliminary surveys of geologic features in the Amerasian Basin.

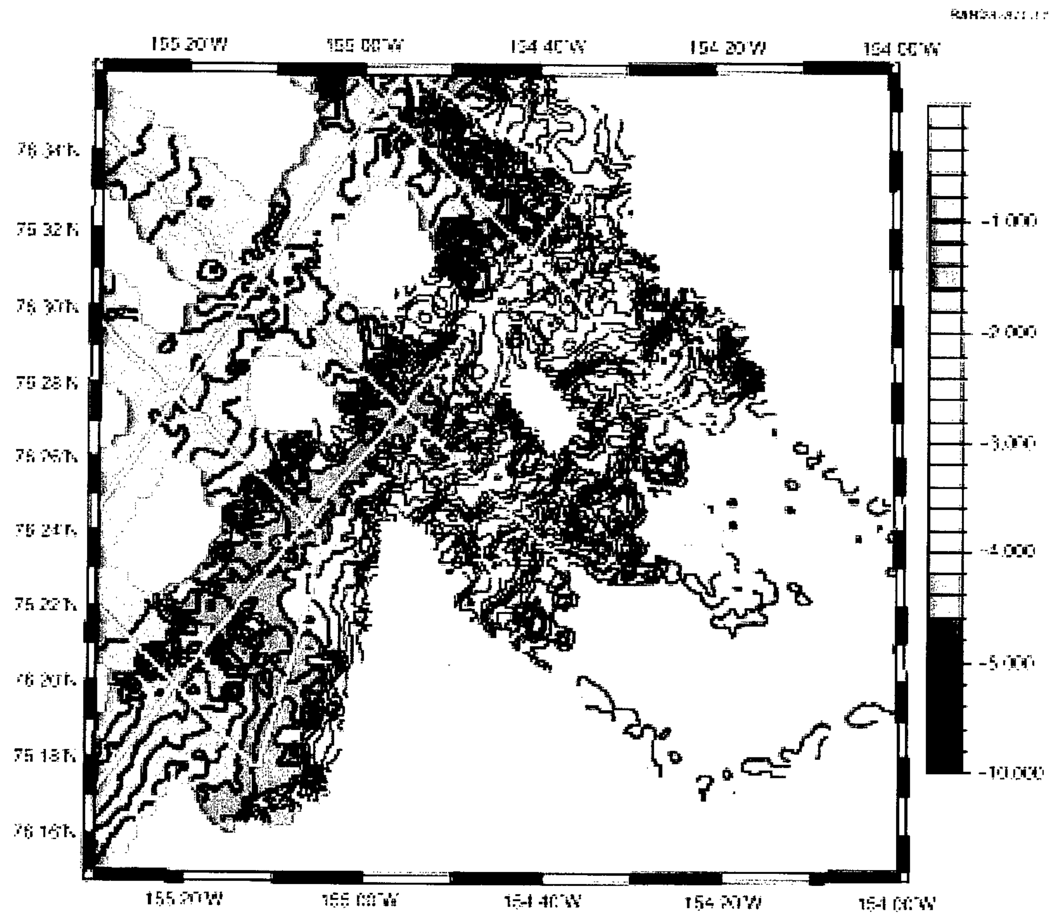

Figure 2.1 Example of swath bathymetric data collected by the SCAMP system collected from the Northwind Rise during SCICEX 99. The white lines show the submarine tracks. The area of the box is approximately 400 km^2. The color scale indicates the depth in meters. Collecting the data required approximately 12 hours of cruising time.

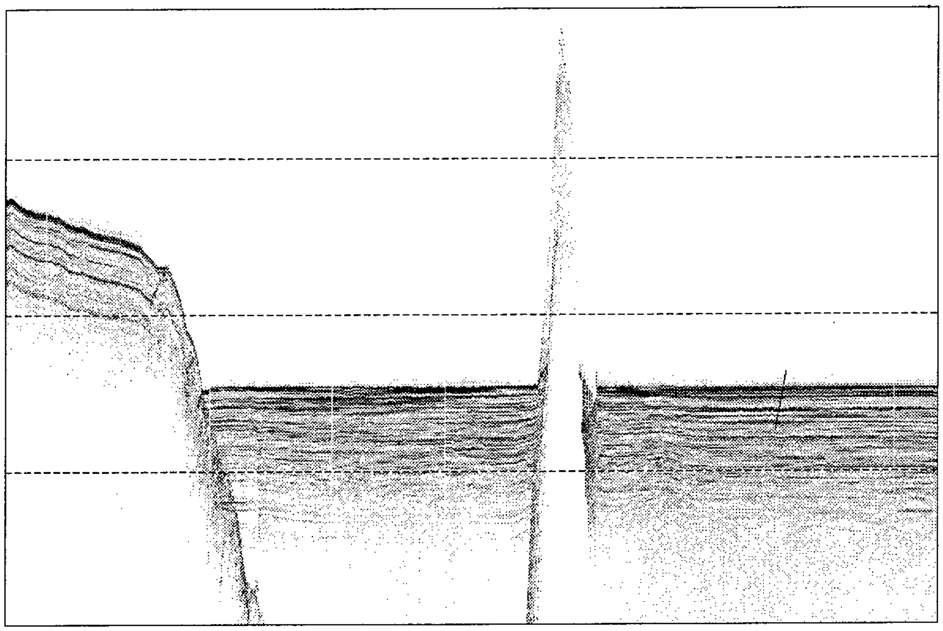

Figure 2.2 Example of the High-Resolution Sub-Bottom Profile data, collected during SCICEX 98. The profile is between 3,600 and 4,100 m depth and shows penetration depths of 100 m over the section. The vertical resolution is approximately 20 cm.

Temperature-Salinity Profiles

Temperature-salinity profiles are easily collected from the submarine, using two approaches: a sail-mounted CTD sensor that provides a continuous measure of the water properties at the cruising depth, and expendable XCTD sensors, launched from the submarine to provide continuous data from approximately 10 m to a maximum depth of 1,000 m. The SCICEX 2000 workshop report emphasized the need to increase the precision of these sensors to resolve subtle salinity and temperature changes below 200 m. There is also a need to increase the capability for making accurate measurements in the halocline layer between the ice and the submarine. Temperature-salinity profiles across the Arctic Basin have been used to map large scale hydrographic features and evolving changes associated with the mixing of the Atlantic and Pacific oceans and freshwater inflows.

Water Sampling for Chemical and Microbiological Analysis

The SCICEX cruises utilized preexisting intake valves on the submarine to collect water samples for a broad range of analyses. In general, the samples were stored for later laboratory analysis. For some measurements, the samples had to be frozen for storage (e.g., nutrient studies). Presumably, these procedures would continue on a scientific submarine, given the limitations on laboratory space and the controlled atmosphere on a submarine. To sample across the entire range of the submarine cruising depth (50–243 m), some of the SCICEX missions performed downward spiral maneuvers through the water column. To improve the water sampling capability on SSN 686, the scientific community has proposed a continuous flow-through manifold. The goal is to increase the use and flexibility of in-line sensors that would reduce the need for laboratory analysis and sample storage. It would also improve the precision of the sampling within the water column (a cylindrical volume of water). Such a manifold has been designed, though never implemented. It is included in the proposed conversion activities for SSN 686.

There have also been proposals to expand the submarine's sampling capability beyond its cruising depth. During the SCICEX program, this limitation imposed by cruising depth was overcome by surfacing the submarine and establishing ice stations to lower sampling devices on a winch. Given that this procedure is cumbersome, potentially damaging to the submarine, and costly in time, there is broad interest in developing the capability for underway sampling. Two strategies have been suggested, utilizing Niskin bottles or a continuous sampling tube extended from the submarine. The SCICEX community recognizes that these devices would require significant engineering modifications and may require significant experimentation. Specifically, the techniques would require the exchange of large sample bottles through a dirty and potentially vulnerable part of the pressure hull (the trash disposal unit). They would also require operations with a long cord dangling from the submarine hull. These capabilities may be developed over time, but given these potential difficulties, we do not consider the potential for deep sampling as a currently available capability of a scientific submarine.

Measurements of Current

During SCICEX, horizontal currents on top of the submarine were routinely measured using an upward-looking Acoustic Doppler Current Profiler. By mounting a similar sensor on the bottom of the submarine, these measurements could be extended 450 m below the cruising depth. With electrical modifications, and new sensor designs, it would be possible to deploy expendable Doppler current profilers, much like the XCTDs that are used for temperature and salinity. These would extend the measurement range to approximately 1,000 m depth. However, these data may be affected by the submarine's wake in the vicinity of the cruising depth. It is also possible to measure the long wavelength current field at the cruising depth by calculating differences in the ship's speed and heading from the electromagnetic speed log.

Ice Draft Measurements and Ice Mapping

During the SCICEX missions, ice draft was measured using the ship's Digital Ice Profiling System, an upward-looking sonar system that measures the return-time from the ice reflection. To interpret these data and estimate ice thickness, addition information is needed on the submarine location and depth and the acoustic velocity in the overlying water. Based on the SCICEX mission experience, the scientific community has identified a number of tasks to improve the quality of these ancillary data. In addition, a new ice mapping approach has been proposed to provide a three-dimensional image of the underside of the ice. Analogous to the SCAMP system, it would be a multibeam swath mapping sonar system, operating at 150 kHz. It would map 500 m–wide swaths from a depth of approximately 150 m. Such an ice mapping system was deployed for the precursor to the SCICEX missions (the classified ICEX mission). The SCICEX 2000 Workshop Report states that the original system could be refurbished and reinstalled for approximately $350,000. The Arctic Submarine Lab also reports that it is designing a new ice mapping unit that would be hardened to withstand submarine surfacing through the ice.

Seismic Refraction and Reflection

Seismic refraction and reflection measurements have been proposed, using the submarine's towed sonar array as the receiving element. The goal is to obtain information about the geologic substructure below the 100 m depth that can be imaged with sonar reflection from the Sub-bottom Profiler. These measurements would be carried out in tandem with an air gun which would provide a sound source for the seismic measurements. The maximum distance between the submarine and air gun would be approximately 50 km. The air gun could be flown to ice camps or transported on an icebreaker. In the latter case, the spatial extent of the measurements would be limited by the icebreaker.

Optical Properties of the Water Column; Ambient Light Data

These data can be collected using sail-mounted photometers and fluorescence units and by measurements on water samples collected from the flow-through manifold. Installation of an upward-looking photometer has been proposed for future submarine missions. A sail-mounted fluorescence unit was used on the SCICEX cruises.

Biological Monitoring via Sonar

There have been proposals to use the submarine's sonar system to track and characterize undersea populations ranging in size from whales to zooplankton and krill. Such measurements, involving active and passive sensing, should be feasible, if the scientific community is provided full access to the onboard sonar systems. These measurements have not been performed on the SCICEX cruises.

Gravity and Magnetics Measurements

Using towed sensors, it would be possible to carry out surveys of the local gravitational potential and magnetic field. Gravity surveys were performed during SCICEX. To acquire magnetic data would require the installation and calibration of a submarine magnetometer. According to the SCICEX 2000 report, this task may be moderately difficult.

How Do Submarine Capabilities Compare with Those of Other Platforms?

For each of the above measurements, we compare the submarine's capability to other platforms that may be able to collect similar data. In this section we focus on the capabilities of currently available platforms. These include icebreakers, oceanographic research vessels, satellites, ice camps, remote buoys, AUVs deployed from ice camps and icebreakers, airplanes, and facilities for acoustic propagation measurements.

Icebreakers. The U.S. Coast Guard currently maintains three icebreakers that are capable of conducting scientific research in the central Arctic: the *Polar Sea*, the *Polar Star* and the *Healy*. The *Polar* class vessels were built in 1976 and 1978 and retrofitted for scientific operations. The *Healy*, which will have its first research mission in 2001 was specifically designed to support scientific research. Under multiyear ice conditions, these vessels must be escorted by another icebreaker. The *Healy* has a science complement of up to 50 people, 3,800 square feet of lab space, and can transit through four-foot-thick ice at roughly 3 knots. In addition to the USCG icebreakers, there are two additional U.S. vessels with less icebreaking capability (*Nathaniel Palmer*, *Helix*) and 80 international ice-capable ships.

Oceanographic research vessels are deployed within the privately and federally owned Academic Research Fleet. The vessels are operated by academic institutions. The fleet consists of large ships for ocean-wide investigations, intermediate size ships for regional investigations, small ships for coastal and estuarine work, and platforms with special capabilities such as the submersible Alvin. NSF provides a majority of the support for the operation, maintenance, and upgrade of the Academic Research Fleet. The U.S. Navy and the National Oceanic and Atmospheric Administration (NOAA) are the other major users of the Academic Research Fleet.

Satellites. A number of satellite systems also provide valuable data for Arctic research. These include various forms of imaging (multispectral, radar, etc.), GPS, communications for data, and laser altimetry.

Aircraft are useful for geophysical surveys over broad regions of the Arctic (geomagnetics and gravity). Helicopters can be used to service ice camps in remote locations. Most icebreakers carry at least one helicopter for operations surrounding the vessel.

Ice camps are the simplest and perhaps lowest cost platform for some applications. The camps are usually put on site, supported, and removed by airplanes or helicopters. Details of the ice camp design and the costs depend on the length of the mission, the scale of the research (e.g., entire year versus seasonal), and the support requirements. A large-scale ice camp used for the Surface Heat Budget (SHEBA) project is described in Appendix C. Because ice camps drift with the ice, they cannot be used to study a specific feature or location.

Remote, fixed buoys are used to collect long-term data at sites that are not at risk from ice movement at a fraction of the cost of manned systems. Examples of buoy measurements include ice thickness, water temperature, salinity, air temperature, and atmospheric pressure. Buoy data can be transmitted by satellites or radios, or can be retrieved from onboard storage. Drifting buoys can be tracked by GPS to give a measure of currents or ice motions.

Acoustic propagation experiments use a fixed source and a receiver to measure the acoustic travel time over a known distance in the ocean. With these data one can determine an average acoustic velocity of the water column, which constrains the average temperature and salinity along the propagation path. Examining the frequency content of the signal provides additional information about ice thickness for propagation experiments in ice covered seas. Acoustic propagation measurements can be carried out over large distances in the oceans (thousands of kilometers) because of the nonattenuating properties of water.

AUVs/ROVs. Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs) are small robotic vehicles that can be deployed from ships, submarines, ice camps, and helicopters to collect data. ROVs are tethered to manned platforms for power and control. They have been successful in a variety of hazardous applications, such as underwater salvage. AUVs are designed to be self-contained in terms of power and navigation. Current AUVs have a length of one to two meters, can operate at depths up to several thousand meters, and have ranges of up to 1,000 km.

We compare these platforms to a science submarine with missions profiles similar to the SCICEX models. As described in detail in Chapter 4, such a submarine would carry approximately 15 civilian scientists on board, traveling at maximum speeds of 25 knots anywhere with water depths greater than 100 m. The dedicated scientific submarine would follow a track dictated by scientific needs. We assume three cruises per year of 40 days.

In this analysis, we emphasize *relative* comparisons between the measurement capabilities of the different platforms to identify the incremental benefits of deploying a dedicated science submarine. To carry out this analysis, we define the submarine's capability as the standard for each of the measurement tasks. Then we evaluate the capabilities for the alternative platforms, according to the following scale:

- Enhanced capabilities compared to a submarine
- Equivalent to submarine capabilities
- Degraded capability compared to a submarine
- Some features are degraded; others are enhanced compared to a submarine
- No capability to perform the measurement.

The results are illustrated for two cases: research in the Arctic Ocean and research in the ice-free oceans.

Measurements in the Arctic Ocean

Table 2.1 compares the scientific measurement capabilities of SSN 686 in the Arctic Ocean with a variety of other platforms. The table compares each platform's ability make the nine measurements discussed above and the ability to operate in multiple seasons and in adverse weather.

In the Arctic Ocean, SSN 686 would navigate freely in regions deeper than 100 m during all seasons and in all weather conditions, collecting large amounts of high-quality data. The comparison in Table 2.1 thus suggests that for most "survey" experiments the submarine has a strong advantage compared to other platforms. A submarine is unique in its capability to collect large amounts of bathymetric and synoptic hydrographic data over the entire Arctic Basin, especially in the winter. A submarine also has unique capabilities to collect controlled seismic refraction and reflection surveys along with co-registered geophysical data (e.g., bathymetry, magnetics, gravity, etc.).

For certain measurements, the submarine's advantage depends on the details of the research problem (i.e., what types of data are needed for a specific problem). Measurements of ice draft are an excellent example. Using the submarine's topsounder, SSN 686 could collect ice draft data with high spatial resolution over broad areas. Using a specially installed upward-looking sonar,

Table 2.1 Platforms and Comparison of Current Capabilities for Scientific Measurements in the Arctic Ocean

			Type of measurement								
Platforms	Weather	Seasons	Bathymetry and bottom profiling via sonar	Water sampling for chemical and microbiological analysis	Temperature and salinity profiles	Gravity and magnetics measurements	Seismic refraction	Biological monitoring via sonar	Ice draft and structure	Measurements of current	Optical properties of the water column; ambient light levels
Submarine	Any	All	Broad areas with high S/N	Broad areas at cruising depth, marginal labs	Broad areas to 1,000 m	Broad areas, with high S/N; coregistered with bathymetry	Broad areas with high S/N	With tracking over broad areas	Over broad areas	Over broad areas at cruising depth	Over broad areas at cruising depth
Satellite	Any for radar and gravity measure-ments	All	No	No	No	Limited gravity at long wavelengths	No	No	Limited to <2 m with radar imaging	No	No
Airplane	Limited in bad weather	All	No	No	To ~1,000 m depth over open leads	Over broad area; reduced S/N*	No	No	Limited to <1 m using electromagnetic induction	No	No
AUV/ROV deployed from ice camp or icebreaker	Any**	All**	Limited area; best with ROV	Limited capability	To sea floor; over cruising range	Magnetic surveys feasible over cruising range;* gravity under development	No	Proposed	High resolution, over cruising range	To sea floor over cruising range	To sea floor over cruising range
Acoustic propagation	Any	All	No	No	Average temp over transect only	No	No	No	Average thickness over transect	No	No
Icebreaker	Limited in bad weather	Summer	Limited area; decreased S/N	Limited area; samples to sea floor, best labs	Limited area; feasible to sea floor	Limited area; decreased S/N	Limited area and control; decreased S/N	Limited area, no tracking; adverse noise	Over limited area	Limited area; feasible to large depths	Limited area; feasible to sea floor
Remote buoy	Any	All	No	No	Temporal, at a point	No	No	No	Temporal, at a point	Temporal, at a point	Feasible, at a point
Ice camp	Any	All	Local	Local, to sea floor, poor labs	Local, to sea floor	Local	Local	Proposed, no tracking	Local	Local	Local properties to sea floor

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* Does not include bathymetry which is needed to reduce data to define real geologic structure of undersea landscape.
** In Arctic environment, current AUV/ROV technology would require a host platform which makes it no more capable than ice camp or icebreaker with respect to weather and seasonal aspects.

Equivalent to submarine | Degraded capability compared to submarine | Enhanced and degraded compared to submarine | No capability | Enhanced capability compared to submarine

Table 2.2 Platforms and Comparison of Current Capabilities for Scientific Measurements of the Ice-Free Oceans

Platforms	Weather	Seasons	Type of measurement							
			Bathymetry and bottom profiling via sonar	Water sampling for chemical and microbiological analysis	Temperature and salinity profiles	Gravity and magnetics measurements	Seismic refraction	Biological monitoring via sonar	Measurements of current	Optical properties of the water column; ambient light levels
Submarine	Any	All	Over broad areas with high S/N	Over broad areas at cruising depth	Over broad areas	Over broad areas	Over broad areas	Over broad areas	Over broad areas at cruising depth	Over broad areas
Satellite	Clouds can limit sensor performance at visible wavelengths	All	Global coverage feasible at longer wavelengths	No	Global sea surface temperatures	Yes to gravity at long wavelengths**	No	No	Global on the surface	No
Airplane	Limited in bad weather	All	No	No	To ~1,000 m depth	Over broad areas	No	No	No	No
AUV/ROV deployed from surface ship	Limited in bad weather	All	Yes, over limited areas; most feasible with an ROV	Limited capability	Up to 6,000 m depth; over cruising range	Magnetic surveys feasible over cruising range*	No	Yes	High resolution, over cruising range	Feasible to 6,000 m depth over cruising range
Surface ships	Limited in bad weather	All	Yes	Measurements to large depths; best chemical laboratories	Measurements to large depths	Yes	Yes	Yes	Yes to large depths	Yes
Remote and/ or drifting buoys	Any	All	No	No	Temporal over broad areas with multiple instruments	No	No	No	Temporal over broad areas with multiple instruments	Feasible at a point

* Bathymetry is needed to get true magnetics.

** Current AUV/ROV technology would require a host platform which makes it no more capable than surface ship with respect to weather and seasonal aspects.

RANDMR1369.0.T2.2

Equivalent to submarine | Degraded capability compared to submarine | Enhanced and degraded compared to submarine | No capability | Enhanced capability compared to submarine

it could also make a detailed topographic map of the underside ice morphology in selected areas. However, there are additional techniques for collecting data on ice draft and thickness that could also make an important contribution to climate change research in the Arctic. For example, upward-looking sonars have been moored in the Arctic Basin, providing a time-resolved measurement of the ice draft as it drifts overhead in varying directions at varying speeds. Acoustic propagation experiments have also been used to estimate changes in the ice draft averaged over the propagation path. They can also be used to estimate changes in average ice thickness over seasonal cycles. And radar satellite imagery can be used to estimate ice thickness less the 2 m over all seasons and weather. Clearly, the submarine ice draft data have unique qualities. However, the benefit of these data compared to other platforms depends on the specific match between the data characteristics and the research needs. These types of issues are addressed in Chapter 3.

In some cases, non-submarine platforms provide data that are unique compared to those submarines can provide. In general, these involve time-resolved measurements (e.g., of ice draft, temperature and salinity at a fixed moorings, currents at a point), and sampling and measurements over the entire water column of the Arctic Ocean. Because the overall platform capabilities can be limited compared to a submarine (e.g., for an ice camp), we denote these cases as a mix of degraded and enhanced features. In these cases, the platform's benefit also depends on the research needs.

Technological advances may affect the relative assessments in Table 2.1. For instance, the deployment of an effective deep water sampling capability on the scientific submarine would increase its capabilities for chemical and microbiological analysis of the water column compared to icebreakers and ice camps. Alternatively, the submarine's currently unique capabilities might be equaled or surpassed by advances in AUV technology for many measurement categories. We will consider the potential impacts of improvements in AUV technology in Chapter 3.

Measurements in the Ice-Free Oceans

Table 2.2 compares the measurement capabilities of SSN 686 with those of a variety of other platforms in the world's ice-free oceans. The table compares each platform's ability make the nine measurements discussed above and the ability to operate in multiple seasons and in adverse weather.

In the ice-free oceans, the submarine's unique capabilities are reduced significantly because of the enhanced capability of surface ships, satellites, and drifting buoys. Without the limitations of an ice cover, ships have greater navigational capabilities, satellites can image a range of ocean properties over vast areas, and buoys can drift great distances. Under these circumstances, the submarine's primary strength involves data gathering in remote regions, rough seas, and bad weather and the submarine's quietness. For instance, even in open oceans some satellites measurements are limited by cloud cover and host platforms for current AUVs can be limited by storms. However, unique submarine capabilities in the open ocean are fewer than in the Arctic because of ongoing technological advances in remote data-collection systems. For example, the Array for Geostrophic Observations is currently being deployed with 3,000 autonomous floats distributed throughout the world's oceans. These will provide approximately 100,000 temperature-salinity profiles and velocity measurements per year, with all of the data publicly available in near real time over the Internet, and shown in Figure 2.3.

In the next chapter, we examine the degree to which the unique submarine capabilities we have identified can contribute to priority research tasks.

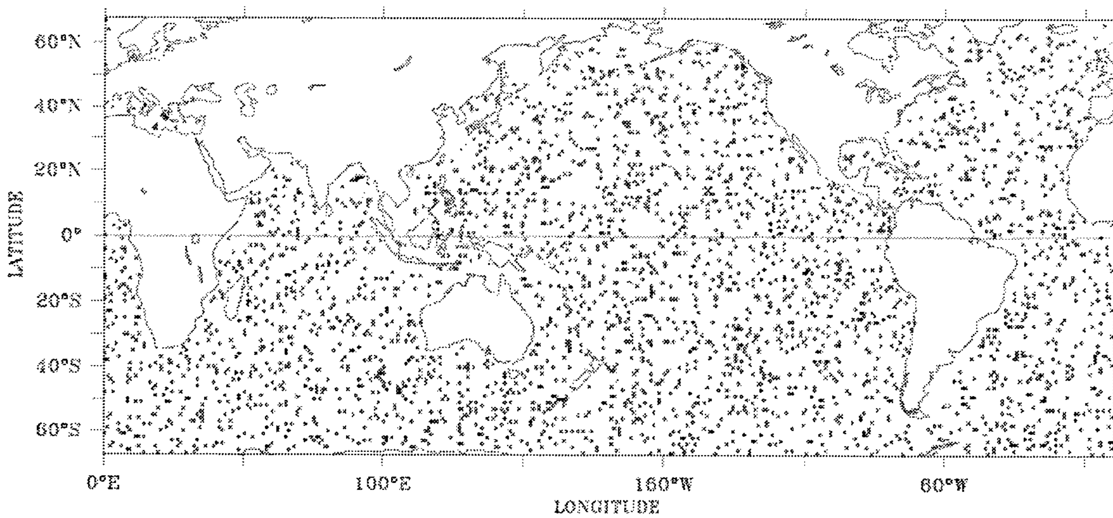

Figure 2.3 The Array for Real-Time Geostrophic Oceanography will include approximately 3,000 automated profiling temperature/salinity sampling floats, deployed evenly over the global ocean, profiling to the sea surface every two weeks and measuring absolute velocity at 1,500 m depth.

Chapter 3: A Science Submarine's Contribution to Priority Research Areas

In the previous chapter, we identified the unique measurement capabilities for a scientific submarine compared to a range of alternative research platforms in the Arctic Ocean and the ice-free oceans. We found that a submarine is unique in its ability to collect high-resolution bathymetric, seismic refraction and reflection, and hydrographic data over the entire Arctic Basin without regard to weather, rough seas, or seasonal changes in the environment. In this chapter, we assess the scientific impact of these capabilities. Consistent with the NSF-planning approach for large facilities we assess these capabilities against the needs of priority scientific agendas. To carry out this analysis, we define the research environment for a submarine by examining a hierarchy of research tasks within the topical areas discussed in the previous chapter. In doing so, we try to answer specifically

- How do current research needs motivate submarine research?
- Considering these needs, what is the specific need for information gathered by a submarine, as opposed to information that might be obtained from other platforms?
- What would be the submarine's contribution to top-level research goals, compared to complementary research activities on different problems, using different platforms or techniques?

Using consensus research agendas, we develop structured problem-solving frameworks in the four research areas discussed in the previous chapter: Arctic climate change and its relationship to global climate change; geologic and geophysical exploration in the Arctic Basin; and understanding the dynamics of the Bering Sea ecosystem.

Following this discussion, the potential submarine contributions to Oceanographic Studies in the Ice-Free Oceans are dealt with separately. The goal of this exercise is to illustrate submarine's scientific impact through its contribution to the natural hierarchy of research tasks within each of the research areas. To carry out this work, we borrow heavily from RAND's strategy-to-tasks analysis (STT),[1] developed to link top-level policy objectives to a wide range of operational tasks. For our analysis, we are interested in the link between top level program goals, scientific questions, and prioritized research tasks.

Because of the interdisciplinary quality of submarine data, this will be an original analysis. Typically, large research facilities are considered against the prioritized needs as defined by individual disciplines (e.g., for a specific type of telescope, or a high-energy particle accelerator). Often, this analysis is coupled to the design process, in which facilities are developed with specific capabilities addressed to specific problems. By comparison, past proposals for a scientific submarine have been largely opportunistic, emphasizing potential windfalls to civilian research to be derived from systems and capabilities intended for military missions (i.e., "swords into plowshares"). To support decisionmaking for civilian expenditures on a scientific submarine program, there is a need for a new approach that evaluates a submarine's contribution to established research goals.

To carry out this analysis, we summarize for each of the three priority research areas the high-level scientific objectives, the strategy the scientific community has chosen to pursue these objectives, and the scientific questions that motivate the key research tasks needed to implement the strategy. We then list the research tasks (i.e., data gathering, analysis, modeling) needed to support the objectives. We draw information from the consensus research agendas of the scientific community. In some cases, there is a natural progression, or hierarchy, to the research tasks (e.g., data gathering that must precede other efforts). In other cases, there is a synergy among the research tasks, allowing diverse approaches to accomplish the top-level objectives. This analysis results in a comprehensive mapping of the research environment where a scientific submarine would operate. In our discussion, we refer to this mapping as the strategies-to-tasks framework for the research area. Using this framework, we characterize the submarine's contribution to priority research areas by assessing its contribution to each of the research tasks. Because the submarine's uniqueness is the primary consideration for the benefits analysis, we rank the submarine's contribution to each task according the following scale:

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[1] David E. Thaler, "Strategies-to-tasks: a framework for linking means and ends," RAND/DRR-243, 1993, 39 pages.

- Submarine data applied to this problem have a number of unique characteristics that would be difficult or impossible to match with other platforms (shaded dark green in this chapter's tables and figures).
- Submarine data applied to this problem may have unique characteristics compared to other platforms (shaded green in this chapter's tables and figures).
- Submarine data applied to this problem may be approximated by other platforms, though there may be differences in quality (shaded light green in this chapter's tables and figures).
- Submarine data are not applicable to this problem (not shaded in this chapter's tables and figures).

Viewed in its entirety, this analysis provides a robust framework to assess the relative importance of the submarine's research contributions. For decisionmakers, this is the foundation for the benefits analysis to compare with the cost information in the following chapter.

Geologic and Geophysical Exploration in the Arctic Basin

To construct a strategies-to-tasks framework for Geologic and Geophysical Research in the Arctic, we use the recommendations from the following scientific community reports:

- Opportunities and Priorities in Arctic Geoscience, National Research Council, 1991.
- Arctic Ocean Research and Supporting Facilities, National Research Council, 1995.
- Ocean Drilling Research, an Arctic Perspective, National Research Council, 1999.
- Summary Report, InterRidge Workshop on Mapping and Sampling the Arctic Ridges, 1998.
- Marine Sciences in the Arctic: A Strategy, a Report to the National Science Foundation, 1999.

The research strategy, outlined in these documents, is a straightforward program of baseline data collection. The research questions that drive this effort are quite general, reflecting a need for basic information rather than collecting data to test specific hypotheses or models. As described above, this effort reflects the primitive state of knowledge regarding the Arctic Ocean basin, arising from the logistical difficulties of performing research in ice-covered seas. These issues are reflected in the NSF's program description, soliciting proposals for geologic and geophysical research in the Arctic:

> Research supported by OPP [the Office of Polar Programs] includes all sub-disciplines of terrestrial and marine geology and geophysics. Special emphasis is placed on understanding geological processes important to the arctic regions and geologic history dominated by those processes.[2]

In this setting, the overall topology of the strategy-to-tasks is one-dimensional: there is a single strategy to accomplish the top-level objective, followed by a sequence of research tasks. Without competing strategies, the priorities for research largely reflect the natural sequence for data collection (e.g., site surveys of the ocean basin will precede drilling and sampling efforts). Moreover, there is a direct connection between data collection efforts and the top-level objective, suggesting a simple approach to identifying the benefits for different data acquisition strategies.

Figure 3.1 illustrates a hierarchy that connects a high-level scientific objective—Fill Longstanding Knowledge Gaps Regarding the Arctic Ocean Basin—with the scientific questions that must be answered to achieve this objective as well as to the measurements needed to answer those questions.

The most important feature of the submarine for geological and geophysical exploration in the Arctic is the capability to collect high-resolution swath bathymetry and sub-bottom profiles over the *entire* Arctic Basin. As indicated in Table 2.1, it would not be feasible to collect a data set of this quality and coverage using alternative platforms such as icebreakers and AUVs. For this reason, we indicate unique characteristics for submarine data applied to two of the research tasks in Figure 3.1. A portion of these data was collected during the SCICEX cruises, with important scientific implications. Building on these results, and previous scientific proposals, it has been recognized that high-quality bathymetric data would have a legacy value and it would make a critical contribution to the high-level research objective of filling in long-standing knowledge gaps regarding the Arctic Ocean basin. If one were to map all regions greater than 100 m depth, this would correspond to an area of 3.65×10^6 km^2. Based on the performance of the SCAMP system, this would

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[2] "Arctic Research Program Opportunities," National Science Foundation Program Announcement, 98-72, 1998.

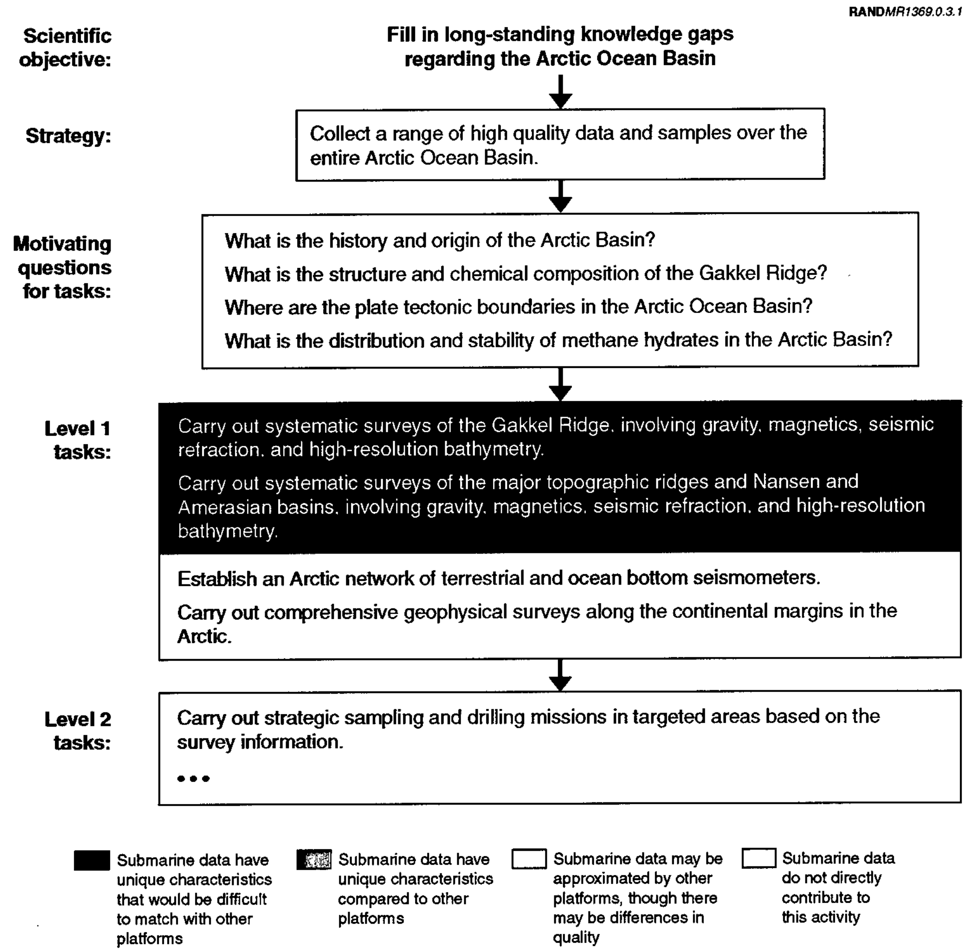

Figure 3.1 Geology and Geophysics Research Objectives and Tasks

require approximately 400 days of data collection. This represents about three years of data collection from a dedicated science submarine.

The submarine's capability to collect seismic refraction and reflection data would also be valuable in this research area, as shown in Table 3.1. While icebreakers have collected these data in the past, a submarine would offer at least one important advantage: the ability to collect data over a continuous region with precise control of the navigational tracks. Submarine gravity measurements would provide higher resolution data, compared to aerial or satellite surveys that are currently available. If these data were collected with bathymetric surveys, it would allow a straightforward and accurate association between the data sets, which is valuable for geologic and geophysical studies in the ocean basins.

Scientific objectives	Research tasks	Submarine measurements								
		Bathymetry and bottom profiling	Water sampling at cruising depth	Temp-erature/ salinity profiles	Gravity and magnetic surveys	Seismic refraction and reflection profiles	Biological monitoring via sonar	Ice draft, structure, and mapping	Measure-ments of current	Optical properties of the water column
Fill in long-standing knowledge gaps regarding the Arctic Ocean Basin	Carry out systematic surveys of the Gakkel Ridge, involving gravity, magnetics, seismic refraction, and high-resolution bathymetry.	X			X	X				
	Carry out systematic surveys of the major topographic ridges and Nansen and Amerasian basins, involving gravity, magnetics, seismic refraction, and high-resolution bathymetry.	X			X	X				

NOTE: Boxes not filled are not applicable to this research objective.

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- (black box) Submarine data have unique characteristics that would be difficult to match with other platforms
- (shaded box) Submarine data have unique characteristics compared to other platforms
- (open box) Submarine data may be approximated by other platforms, though there may be differences in quality
- (open box) Submarine data do not directly contribute to this activity

Table 3.1 Contribution of Submarine Capabilities to Research on Geologic and Geophysical Exploration

In summary, submarine data would make a number of unique and important contributions to Geologic and Geophysical Exploration in the Arctic Basin. The submarine would also have a relatively large relative impact in this field, because of the hierarchy of current research problems.

Climate Change in the Arctic

To construct a strategy-to-tasks framework for Climate Change in the Arctic, we consulted the recommendations from the following scientific community reports:

- *Marine Sciences in the Arctic: A Strategy,* a Report to the National Science Foundation, 1999.
- *Arctic Climate System Study Implementation Plan,* World Climate Research Programme, 1999.
- *Toward Prediction of the Arctic System: Predicting future states of the arctic system on seasonal-to-century time scales by integrating observations, process research, modeling, and assessment; a science plan for the National Science Foundation Arctic System Science* (ARCSS) *Program,* 1998.
- *The Arctic Paleosciences in the Context of Global Change Research,* 1999.

The analysis was also informed by plans for the U.S. Global Climate Change Research Program, which includes research in Understanding the Earth's climate system, biology and biogeology of ecosystems, composition and chemistry of the atmosphere, paleoenvironment and paleoclimate, human dimensions of global climate change, and global water cycle. Each of these areas includes Arctic climate research.[3] We also examined the World Climate Research Program, where the Arctic Climate System Study is one of five major projects. The others include Global Energy and Water Cycle Experiment (GEWEX), World Ocean Circulation Experiment (WOCE), Stratospheric Processes and their Role in Climate (SPARC), and Climate Variability and Predictability (CLIVAR).

While there are a large number of publications outlining climate research issues in the Arctic, we chose the above publications because they articulate organized research plans to be executed by NSF and the international scientific community. In general, these define the top tier of research activities; a large number of research plans have been written to detail the activities outlined in these publications.

Together these publications define a comprehensive, systems-based strategy for studying Arctic climate as shown in Figure 3.2. In this context, "system" refers to the collective interactions and feedback mechanisms between the ocean, sea ice, atmosphere, landmass, biomass, and freshwater that control the Arctic climate. At the center is a focus on modeling, with the goal of developing an improved predictive capability for the behavior of the Arctic climate. In part, the modeling effort is supported by accurate historical data, describing changes in Arctic climate over the past 65 million years. Hence, there is a strategy to document the climate history of the Arctic. To strengthen

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[3]For FY 2000, the National Science Foundation designated $181.7 million as part of the U.S. Global Climate Change Research Program. The Arctic component was included in the Arctic System Science program, with $13.8 million in funding.

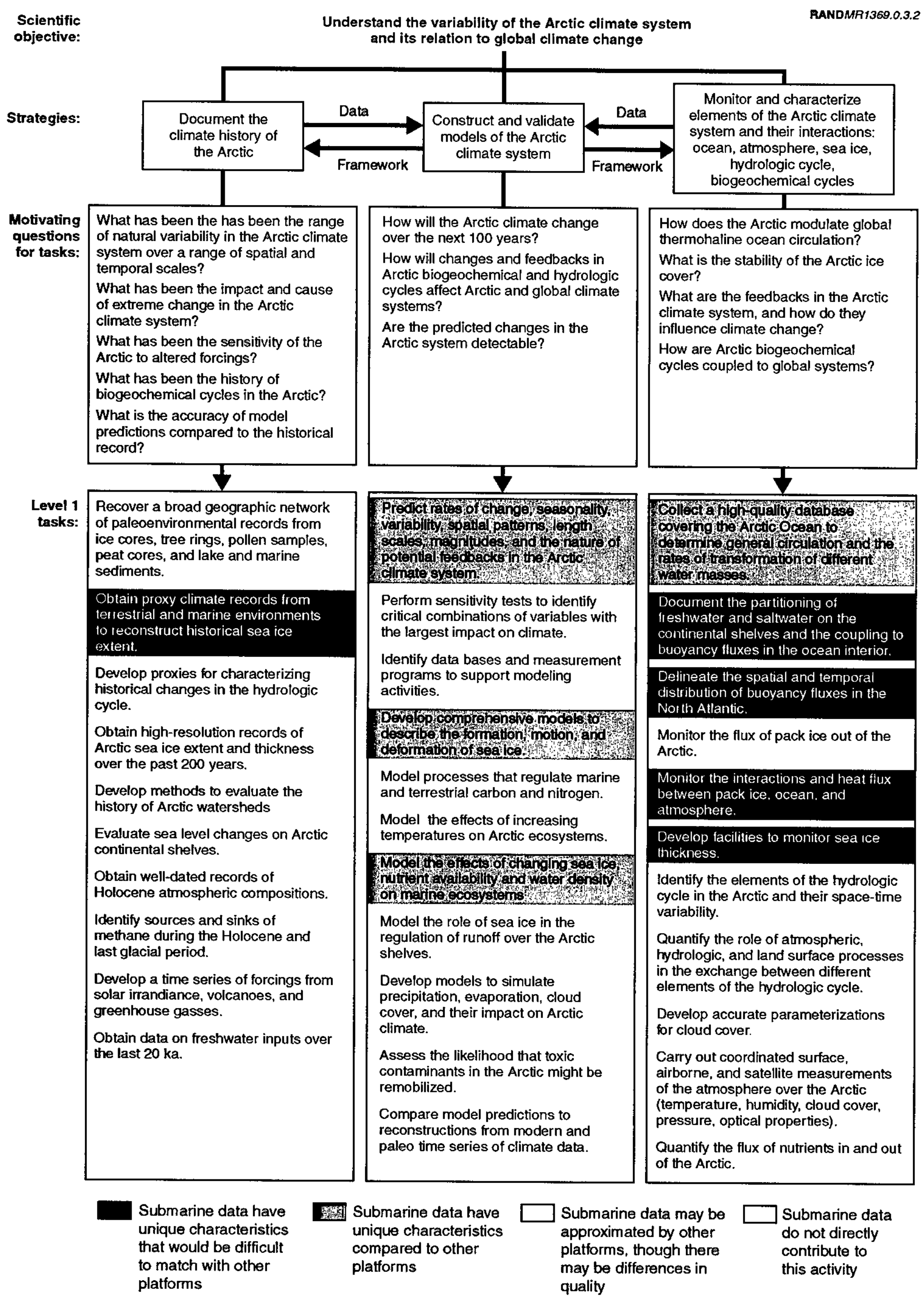

Figure 3.2 Climate Change Research Objectives and Tasks

present-day models, and to provide a basis for future predictions, there is a need for detailed monitoring of the current Arctic climate system. Hence there is a strategy to monitor and characterize elements of the Arctic climate system and their interactions: ocean, atmosphere, sea ice, hydrologic cycle, biogeochemical cycles.

Unlike the framework for geology and geophysics, climate change research in the Arctic requires coordination over a wide range of disciplines and facilities to achieve the top-level objective. (See Appendix C for a discussion of current research activities and infrastructure in the Arctic.) Given the synergy between the research strategies (e.g., data collection and monitoring to support modeling), there is a complex prioritization for individual tasks. In such an environment, additional policy and program concerns play an important role in focusing decisionmaking on individual research efforts and facilities. Important considerations include the opportunities for synergy, balance of funding between disciplines, and maximizing the value of existing facilities.

For climate change research, the most important feature of the submarine is the capability to collect data over broad areas of the Arctic Basin at all times of year. Of particular importance are hydrographic measurements in the upper ocean (temperature/salinity profiles), detailed mapping of ice draft and structure, and high-resolution bathymetric surveys. Applied to the following scientific tasks, submarine data would have unique characteristics with important research implications:

- Document the partitioning of freshwater and saltwater on the continental shelves and the coupling to buoyancy fluxes in the ocean interior.
- Delineate the spatial and temporal distribution of buoyancy fluxes in the North Atlantic and Greenland Sea.
- Monitor the interactions and heat flux between pack ice, ocean, and atmosphere.
- Develop facilities to monitor sea ice thickness.
- Obtain proxy climate records from terrestrial and marine environments to reconstruct historical sea ice extent.

As shown in Table 3.2, the first three tasks involve hydrographic measurements, with spatial mapping of temperature and salinity variations in the upper ocean. For this work, the submarine's mobility and access would be particularly valuable because the research requires data collection over broad areas, under conditions that often preclude surface operations. It is notable that the quality of these submarine data would be inferior to those that might be collected by a surface ship because of differences in the sensor technology between these platforms, as shown in Table 2.1. This comparison

Table 3.2 Contribution of Submarine Capabilities to Research on Climate Change in the Arctic

Scientific objectives	Research tasks	Submarine measurements								
		Bathymetry and bottom profiling	Water sampling at cruising depth	Temp-erature/ salinity profiles	Gravity and magnetic surveys	Seismic refraction and reflection profiles	Biological monitoring via sonar	Ice draft, structure, and mapping	Measure-ments of current	Optical properties of the water column
Understand the variability of the Arctic climate system and its relation to global climate change	Document the partitioning of freshwater and saltwater on the continental shelves and the coupling to buoyancy fluxes in the ocean interior.		X	X						
	Delineate the spatial and temporal distribution of buoyancy fluxes in the North Atlantic.		X	X					X	
	Develop facilities to monitor sea ice thickness.							X		
	Monitor the interactions and heat flux between pack ice, ocean, and atmosphere.		X	X				X	X	X
	Obtain proxy climate records from terrestrial and marine environments to reconstruct historical sea ice extent.	X				X				
	Collect a high-quality database covering the Arctic Ocean to determine general circulation and the rates of transformation of different water masses.	X	X	X					X	X
	Develop comprehensive models to describe the formation, motion, and deformation of sea ice.							X	X	
	Model the effects of changing sea ice, nutrient availability, and water density on marine ecosystems.		X	X			X	X		X
	Model processes that regulate marine and terrestrial carbon and nitrogen.									
	Assess the likelihood that toxic contaminants in the Arctic might be remobilized.									
Understand the variability of the Arctic climate system and its relation to global climate change	Recover a broad geographic network of paleoenvironmental records from ice cores, tree rings, pollen samples, peat cores, and lake and marine sediments.									
	Evaluate sea level changes on Arctic continental shelves.									

NOTE: Boxes not filled are not applicable to this research objective.

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■ Submarine data have unique characteristics that would be difficult to match with other platforms ▒ Submarine data have unique characteristics compared to other platforms ☐ Submarine data may be approximated by other platforms, though there may be differences in quality ☐ Submarine data do not directly contribute to this activity

Note: An x indicates the types of submarine data that are pertinent to specific research tasks.

illustrates the importance of context for the benefits analysis: The potential benefits from a scientific submarine are associated with specific capabilities applied to specific problems.

A number of platforms can collect data to address the fourth task, developing facilities to monitor sea ice thickness. These include moored upward-looking sonar, surface wave propagation experiments, acoustic propagation measurements, radar imagery, and submarine measurements. However, the other platforms have difficulty matching the most important characteristic of the submarine data, which is the capability to make detailed maps of ice thickness across the Arctic Basin. Repeat transects across seasons and years would provide unprecedented fine-scale information for studying the temporal evolution of ice thickness. The fifth problem, obtaining proxy climate records from terrestrial and marine environments to reconstruct historical sea ice extent, overlaps with the Geologic and Geophysical Exploration in the Arctic, as it involves detailed mapping of the ocean bottom to identify features such as glacial scour and paleocurrent indicators.

Within the strategies-to-tasks framework for Climate Change Research in the Arctic, there are a number of areas in which a submarine would contribute, but at a lower level of impact, because alternative platforms would make a comparable contribution to the research task.

Viewed in the broadest perspective, climate change research clearly requires a diverse range of platforms and strategies to achieve the top-level scientific objective. In this setting, the nature of the submarine contributions is also diverse. While the dedicated science submarine would make fundamental contributions for some of the tasks, its impact in other areas would be less profound. Thus, the final assessment of the submarine benefits in this area depends on priorities assigned to these research efforts. Specifically, would the submarine make a unique contribution to high-priority tasks? We assume that this final prioritization would be carried out by the scientific community, working with the civilian science agencies.

Finally, military submarines could also contribute to the measurements needed for climate change research as part of their operational missions. The potential value of these data was emphasized in one of the recommended mission profiles in the *SCICEX 2000* workshop report. For climate change research, the most important data include temperature/salinity profiles measured with expendable probes and ice draft measurements obtained from the submarine's topsounder.

Understanding the Dynamics of the Bering Sea Ecosystem

To assemble a strategies-to-tasks framework for this research area, we used the recommendations and analysis from the following documents

- *Draft Bering Sea Ecosystem Research Plan,* September 1998, Interagency document prepared by NOAA, Department of Interior and Alaska, Department of Fish and Game.
- *The Bering Sea Ecosystem,* National Research Council, 1996.

The interagency Draft Research Plan represents a consensus distillation for a wide range of previous planning efforts. By comparison the National Research Council report describes the scientific challenges for developing a more effective ecosystem management practices. Together, these reports suggest a huge range of research activities which we have distilled, with some abbreviation, in Figure 3.3.

The goal for this research is to collect a large amount of information on the properties of the Bering Sea ecosystem to refine predictive models of ecosystem behavior in response to external changes (e.g., climate change, fishing, changes in species populations). In this case, the application for the models, and scientific understanding is to improve the effectiveness of ecosystem management practices. Like the climate change problem, the tasks span a huge range of disciplines and research activities, suggesting a similar need for coordination and prioritization to increase the effectiveness of the overall research effort.

Table 3.3 Contribution of Submarine Capabilities to Research on the Dynamics of the Bering Sea Ecosystem

Scientific objectives	Research tasks	Submarine measurements								
		Bathymetry and bottom profiling	Water sampling at cruising depth	Temp-erature/ salinity profiles	Gravity and magnetic surveys	Seismic refraction and reflection profiles	Biological monitoring via sonar	Ice draft, structure, and mapping	Measure-ments of current	Optical properties of the water column
Improve the understanding of ecosystem processes in the Bering Sea to support more effective ecosystem management practices	Collect data on ice condiditons and hydro-graphy in the Bering Sea.		X	X				X	X	
	Determine how sea ice, sea surface temperature, and the extent of the cold pool affect the transfer efficiency of primary production to the pelagic and benthic food webs.		X	X			X	X	X	X
	Establish baseline conditions for the physical environment.	X	X	X					X	X
	Monitor contaminant levels (chemical and debris).									

NOTE: Boxes not filled are not applicable to this research objective.

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- (black box) Submarine data have unique characteristics that would be difficult to match with other platforms
- (shaded box) Submarine data have unique characteristics compared to other platforms
- (white box) Submarine data may be approximated by other platforms, though there may be differences in quality
- (white box) Submarine data do not directly contribute to this activity

Note: An x indicates the types of submarine data that are pertinent to specific research tasks.

In this research area, the submarine's strongest feature is its ability to navigate and make measurements under the ice. Similar to climate change research in the Arctic Ocean, there is a need for hydrographic and ice draft measurements in the Bering Sea, as shown in Table 3.3. The principal challenge for this work is that much of the Bering Sea may be too shallow for safe submarine operations (40 percent is less than 100 m deep). In addition to the hydrographic and ice measurements, which were demonstrated during SCICEX, submarine monitoring of biological features would also be unique, if it was performed in ice-covered seas. Examples include water sampling from specific oceanographic features and mapping fish and zooplankton populations using the submarine's sonar systems. In this application the submarine's quietness could add importantly to its data collection capabilities. The last item has been proposed for a scientific submarine, yet it was not demonstrated during the SCICEX cruises. In part, this reflects classification concerns regarding the submarine's onboard sonar systems. With this background, the submarine's primary impact would be associated with the following tasks:

- Collect data on ice conditions and hydrography in the Bering Sea
- Determine how sea ice, sea surface temperature, and the extent of the cold pool affect the transfer efficiency of primary production to the pelagic and benthic food webs.

Given the breadth of the required research effort, the final assessment of the submarine benefit clearly requires a top-level prioritization for all of the research tasks.

Contributions to Oceanographic Studies in the Ice-Free Oceans

Because of the size and scope of this research area, we use a different approach to analyze the potential submarine benefits. As noted previously, Oceanography in the Ice-Free Oceans addresses a diverse research agenda, utilizing a vast array of data collection facilities. Viewed from a top-level perspective of a strategies to task framework, it is difficult to assess to contribution of a single platform (such as a submarine) to such a large research problem. More important, the programmatic decisionmaking in this area is distributed over a much greater number of agencies, disciplines, and stakeholders compared to the other three research problems that we have considered (Climate Change in the Arctic, Geologic and Geophysical Exploration in the Arctic, and Understanding the Dynamics of the Bering Sea Ecosystem).

To consider the potential submarine contributions, we examine the proposed research tasks for a SSN 637-class submarine in the ice-free oceans, identified in the UNOLS report *A Nuclear-Powered Submarine Dedicated to Earth, Ocean, and Atmospheric Research.* Noting the comparisons in Table 2.2, we identify the submarine's potential for unique contributions for each of these problems.

We conclude with observations about the submarine capabilities that would have the largest impact on oceanographic research.

(1) Studies of deepwater formation in the North Atlantic.

This task, which addresses an important question in climate change research, was discussed in the strategies-to-task framework for Climate Change in the Arctic: Delineate the spatial and temporal distribution of buoyancy fluxes in the North Atlantic. As noted in that discussion, a submarine would provide unique data for this problem.

(2) Documenting the evolution of the hydrographic structure of the upper ocean under a hurricane.

While a large number of assets are deployed to measure the properties of hurricanes from above (airplanes and satellites), there is comparatively little understanding of the exchange of energy between hurricanes and the underlying ocean. It has been postulated that such information would improve forecasting models for the strength, evolution, and tracking of hurricanes. In principle, a submarine has a unique capability to collect hydrographic data under a moving hurricane. Clearly, there would be significant logistical considerations associated with these deployments.

(3) Carry out high-resolution ocean acoustics experiments to monitor fronts in coastal waters, internal waves, and ocean bottom reverberations.

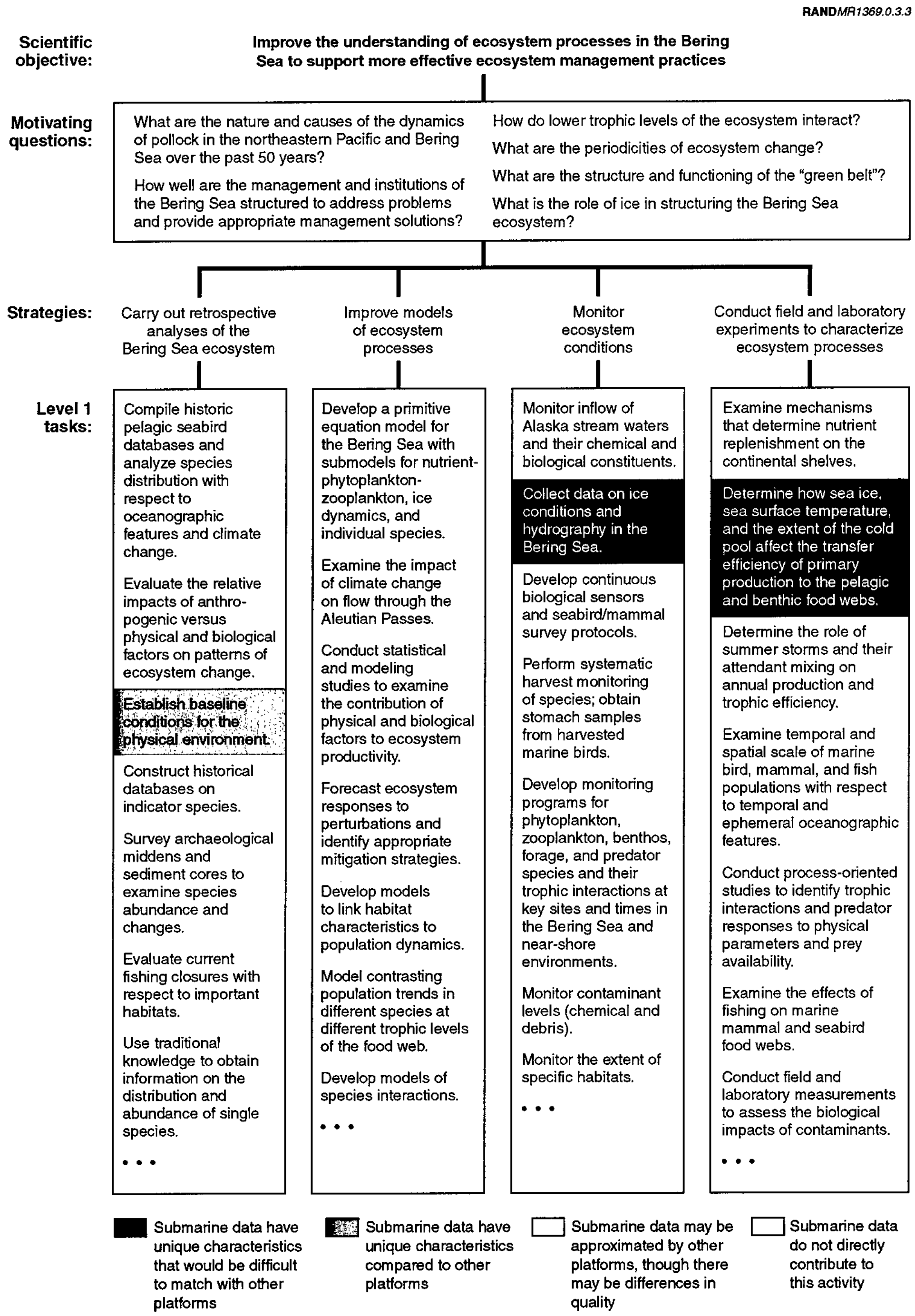

Figure 3.3 Bering Sea Ecosystem Research Objectives and Tasks

The onboard sonar arrays on a nuclear-powered submarine would provide a novel capability for ocean acoustics experiments. Compared to other facilities for acoustic measurements, a submarine has three principal advantages: a large effective aperture for the sonar array, a capability to track hydrodynamic features in the ocean, and low ambient noise levels. To be useful, these measurements would require full access to the acoustic waveforms from the submarine sonar systems. Thus, it may not be possible to perform this research in an unclassified setting.

(4) Carry out geophysical surveys off Antarctica.

Because of the remote setting, and the presence of drifting ice bergs, there have been relatively few geophysical surveys in the seas surrounding Antarctica. In this environment, a submarine would have unique capabilities to collect swath bathymetry and gravity data over broad areas. Working with an icebreaker, it could also collect seismic refraction and reflection data. However, policy concerns associated with the Antarctic Treaty may limit submarine deployments below 60° S. These issues are discussed in detail in Appendix F.

(5) Conduct hydrographic measurements in remote regions, especially south of 60° S.

There is a growing interest in detailed hydrographic data from all the world's oceans to support improved climate and oceanographic models (e.g., temperature/salinity profiles and current data). In remote regions, these data have historically been collected by "ships of opportunity," leading to databases with uneven quality and spatial distributions. Because a submarine can cruise faster than a surface ship (25 knots compared to approximately 15), through all weather, it has been suggested that a submarine could collect high-quality data from under-sampled regions. However, in recent years the unique quality of these submarine data has diminished because of the development and deployment of automated profilers throughout the oceans.

Considering the above issues, the most important feature of the submarine for research in the ice-free oceans is the capability to work in rough seas. Thus, the submarine would make the most unique contribution to the first and second research problems. Similar to the strategy to task discussion, the overall submarine benefit depends on the prioritization for these research efforts by the scientific community and the civilian science agencies.

Additional Considerations

In the preceding discussion, we have considered a submarine's capability to collect a range of scientific data sets against the needs of consensus research agendas. To inform a top-level consideration of the benefits associated with a scientific submarine, this analysis identifies scientific problems where a submarine would provide unique data. In this section, we discuss additional issues which may have some implications for the benefits of a science submarine. These are

- Technological developments in autonomous underwater vehicles (AUVs);
- Existing oceanographic databases; and
- Treaties and international agreements.

In general, these issues have the potential to affect the benefits of a scientific submarine. Specifically, technological advances in ocean sensors may reduce a submarine's unique contributions; international agreements may limit the operations of a nuclear-powered submarine; and newly declassified oceanographic databases may redefine priority research areas and thus enhance or decrease the impact of a science submarine's contributions. Because these effects are difficult to predict, they have not been incorporated in the above analysis of the submarine's contribution to scientific research. However, they may play an important role in the assessment of the submarine benefits, and thus, they are discussed in separate sections below.

Developments in Autonomous Underwater Vehicle Technology

The discussion so far has identified the unique capabilities of a dedicated science submarine given the submarine's current capabilities and that of alternative platforms for Arctic research. The last decade, however, the has seen the rapid development of AUVs, driven by progress in small, cheap and powerful computer technology; artificial intelligence and novel automatic control algorithms, information networking breakthroughs; and new materials for structural and sensor systems. A variety of these self-contained, robotic submersibles have been prototyped and demonstrated, and a few have even performed useful operational missions on an ongoing basis. The rate of progress in these AUV systems suggest that in the future they could potentially collect many of the measurements currently unique to a dedicate science submarine.

Predicting the rate of technological progress is difficult, especially in areas where the state of the art is advancing rapidly. Proponents of these AUV systems suggest that they could provide many of the capabilities we identify as unique to a dedicated science submarine, at a minimum of five to ten years later than such observations would be available with such a submarine. There are significant, ongoing research efforts aimed at developing AUVs capable of long-transect hydrographic measurement in the Arctic Basin. The individual components for this AUV have been successfully tested by researchers at the Monterey Bay Aquarium Research Institute, and a full-scale Arctic field test is scheduled for spring of 2001. Decisionmakers should properly view with some skepticism any claims about the date at which potential revolutionary, but not yet proved, capabilities of new technology systems will become available. Nonetheless, the potential of these AUVs is sufficient to warrant the serious attention of decisionmakers concerned with a dedicated science submarine.

The uncertain, yet potentially significant, future capabilities of AUVs presents decisionmakers with a classic problem of balancing today's "bird-in-the-hand" against potentially promising future "birds-in-the-bush." To frame the contours of this decision, we present a simple scenario analysis as sketched in Figure 3.4. Tables 2.1 and 2.2 described the current capabilities of AUVs as

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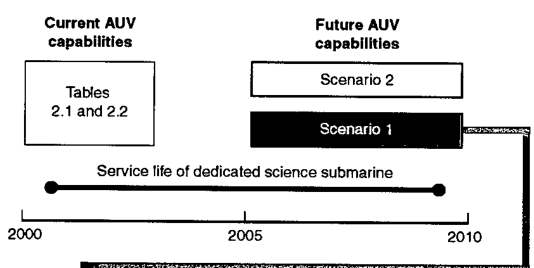

			Type of measurement									
Platforms	Weather	Seasons	Bathymetry and bottom profiling via sonar	Water sampling for chemical and microbiological analysis	Temperature and salinity profiles	Gravity and magnetics measurements	Seismic refraction	Biological monitoring via sonar	Ice draft and structure	Measurements of current	Optical properties of the water column; ambient light levels
Submarine	Any	All	Broad areas with high S/N	Broad areas at cruising depth, marginal labs	Broad areas to 1,000 m	Broad areas, with high S/N; coregistered with bathymetry	Broad areas with high S/N	With tracking over broad areas	Over broad areas	Over broad areas at cruising depth	Over broad areas at cruising depth
Current AUV/ROV deployed from ice camp or icebreaker	Any	All	Limited area; best with ROV	Limited capability	To sea floor, over cruising range	Magnetic surveys feasible over limited areas gravity under development	No	Proposed	High resolution, over cruising range	To sea floor over cruising range	To sea floor over cruising range
Best case AUV/ROV in 2010	Any	Significant improvement possible	Significant improvement possible	Significant improvement possible	Significant improvement possible	Significant improvement possible	Significant improvement possible	Significant improvement possible	Significant improvement possible	Significant improvement possible	Significant improvement possible

Equivalent to submarine — Degraded capability compared to submarine — Enhanced and degraded compared to submarine — No capability — Enhanced capability compared to submarine

Figure 3.4 Comparison of Submarine with Two Scenarios for Capabilities of Future AUVs

understood from actual operational experience. Over the next 10 years, AUVs may or may not acquire a broad range of additional capabilities. Table 3.4 shows two scenarios spanning a range of possibilities, based on forecasts of potential technological trajectories. At one end of the spectrum (labeled Scenario 1), AUV technology will remain relatively unchanged compared to the submarine. At the other end of the spectrum (labeled Scenario 2), AUVs could plausibly exceed submarine capabilities in any and all measurement areas. This end of the spectrum would come about with significant improvements in AUV range and continued miniaturization of onboard instrumentation. These new capabilities could overlap with the lifetime of the *L. Mendel Rivers* as a scientific submarine, or not arrive until after its retirement—if at all.

One of the key factors that will influence whether highly capable AUVs will come about is the level of government support for the development of AUV technology. However, there may be, as in any technology development program, unforeseen technical or operational problems. Thus, in weighing the benefits of a dedicated scientific submarine, decisionmakers must consider the funding that may be available for AUV technology and the rate of advance of that technology against the cost of delay in collecting data on the Arctic. Such delay could be costly if data collected in the near term could cause significant changes in policy toward climate change, fisheries management, or other issues.[4] In the scenario where the rate of technology advance for AUVs is rapid, the unique benefits of the submarine will be relatively less. In the scenario where the rate of AUV technology advance is slow and the cost of a delay in acquiring information is high, the value of the submarine is relatively large. Appendix D provides a review of recent progress in AUV technology, but a full assessment of the costs and benefits of relying on future AUVs as a substitute for a dedicated science submarine is beyond the scope of this study.

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[4]Studies on the value of scientific information to climate change policy (see for instance, S. C. Peck and J. T. Teisberg, "Global Warming Uncertainties and the Value of Information: An Analysis Using CETA," Resource and Energy Economics, 15, 71–97, 1993, or R. J. Lempert, M. E. Schlesinger, S. C. Bankes, and N. G. Andronova, "The Impacts of Climate Variability on Near-Term Policy Choices and the Value of Information," Climatic Change, 45:129–161, 2000) suggest that the value of such near-term information can be on the order of several tens of billions of dollars. It is important to note, however, that such studies address the aggregate benefit of all scientific information on climate change, not information on climate change in the Arctic.

Existing Oceanographic Databases

The existence of a substantial body of previously classified data on the Arctic region could also influence the benefits of a dedicated science submarine. Much of this data has been collected by Navy submarines over the past three decades. These data are only now being declassified, converted to digital format, and analyzed. A clearer understanding of what data already exist could affect an assessment of the need for a dedicated science submarine.

How might these data affect the potential benefit of a science submarine? Since virtually all of these data are time sensitive, it is unlikely that their availability would preempt the need for the kind of data gathering missions a dedicated science submarine could perform. Instead, the most likely effect would be to redefine critical polar research areas, which could alter the fit between a submarine's unique capabilities and the scientific community's priority research agenda. Knowledge about the Arctic environment could be enhanced substantially and previously undiscovered or poorly understood problems or conditions could displace other issues at the top of the research agenda.

Historically, scientific databases of the world's oceans have been sparse and uneven because of the sheer size of the areas involved, the cost of operating many platforms, and the remoteness or extreme weather conditions of many locations. Additionally, a second challenge has been archiving, consolidating, and distributing the vast amounts of data that could be made available. Two recent developments are rapidly changing this situation. The first is the great concern within the last decade about global climate change, which has resulted in a concerted international effort to collect and archive oceanographic data over the entire globe. At present, considerable progress has already been made on defining and implementing the technical systems necessary to carry out such ongoing global synoptic observations, for example through the United Nations' Global Ocean Observing System and Global Climate Observing System programs. Within the United States, the U.S. Global Change Research Program has spurred the collaboration of many diverse efforts among federal, private, and academic institutions to build an integrated ocean observing system, and much of this is now largely being guided by the National Oceanographic Partnership Program. A large part of this effort is devoted to designing state-of-the-art integrated data management and distribution systems. As part of this, significant effort has been directed toward centralizing the archiving of previously recorded databases, much of which have not hitherto been publicly available.

The second major development concerning oceanographic databases has resulted from the information-technology revolution. The advent of cheap, high-speed processors, large memory capacities, new storage devices such as CDs, and large bandwidth communication systems and satellite links are revolutionizing the capacity for recording, storing, and transferring data. In particular, the rapid development of the World Wide Web has made it possible to archive and distribute large volumes of data publicly with ease. In fact, most U.S. national earth science databases, and many of the international ones, are already accessible from centralized Web sites, and further consolidation is continuing at a rapid pace, with search engines and depositories for "metadata" (i.e., data about data) now becoming widespread as well.

While it is uncertain just how much these data will add to scientific knowledge of the Arctic region, we do know that with the exception of certain kinds of mapping information, all of the newly declassified data are time sensitive. That is, their existence is not likely to preempt the need for updated measurements in the same areas. Furthermore, the kind of high-resolution bathymetric mapping that represents one of the submarine's unique capabilities is unlikely to be duplicated in any of the data now being released, for the simple reason that the technology for high-resolution bathymetric mapping did not exist when these data were created.

International Treaties Governing Antarctica

A final caveat involves political considerations associated with Antarctica. Though we have not considered them in this study, there are potential scientific benefits to using a dedicated scientific submarine to perform oceanographic and geophysical research in the oceans surrounding Antarctica. Scientific studies, and exploration in general, of this region are sparse and have been historically hampered by its remoteness and extreme weather conditions. The physical conditions in the seas surrounding Antarctica are in fact so hazardous that large areas are bathymetrically uncharted, and even the location of the continental margin is unknown in places. Operation of surface research vessels is often restricted to only a few months per year. While it would be feasible for an SSN 637-class submarine to operate in these waters, there could be important policy implications that would limit these operations because of requirements from the Antarctic Treaty, as discussed in Appendix F.

Chapter 4: Estimated Costs of a Science Submarine

The costs associated with an SSN 637-class submarine are an important factor in considering whether to deploy such a vessel as a dedicated science submarine. In this chapter, we estimate these costs. Our cost analysis addresses the following questions:

- What are the costs of operating, maintaining, and providing scientific support for an SSN 637-class nuclear submarine used as a dedicated platform for scientific, non-military research?
- What are the components these costs?
- How do these estimated costs compare with current NSF expenditures for polar exploration and Arctic research?

Key Assumptions Underlying the Cost Analysis

This study's cost analysis rests on several key assumptions. First, we focus on a dedicated science submarine, with mission profiles similar to the SCICEX model. We assume such dedicated science submarine would conduct missions similar to the Dedicated Science Missions of past SCICEX cruises as detailed in *Arctic Ocean Science From Submarines: A Report Based on the SCICEX 2000 Workshop*.[1] Such a submarine would carry civilian scientists on board and follow a track dictated by scientific needs for days or weeks at a time. Second, we examine a specific hull, the USS *L. Mendel Rivers*, SSN 686. Although recently decommissioned on January 1, 2001, this boat retains a significant quantity of nuclear fuel and appears to be the only viable candidate for conversion to a dedicated scientific mission. We also assume the *Rivers* would be retired in 2008 when its nuclear fuel would be expended, assuming continued military tempo operations. Therefore our cost analysis has a fixed time horizon and does not consider costs of refueling.

Third, we assume the dedicated science submarine would be operated by a Navy crew, consistent with current practice for all naval nuclear-powered

[1] *Arctic Ocean Science From Submarines; A Report Based on the SCICEX 2000 Workshop*, 24 pages and 7 appendices, April 1999.

submarines, and would be subject to all applicable U.S. Navy requirements. The Navy would retain final authority over the operations, maintenance, and safety requirements for the submarine. Nonetheless, the costs considered here apply only to non-warfighting capabilities. Finally, we assume that all of the submarine maintenance work would be performed by military or civilian yards qualified for SSN 637-class submarines.

Fourth, our analysis requires that we remove 20 members of the Navy crew from the submarine to accommodate the scientific crew and modifications. Specifically, the science crew would occupy an existing Navy bunk room that is forward of the torpedo room where the scientific facilities would be installed. We have made an effort to identify nonessential crew who could be removed, and we have calculated the cost implications. However these crew reductions have not been officially reviewed by the Navy.

Fifth, we identify several potential opportunities for cost sharing between the civilian science community and the Navy that would lower the cost of the science submarine to the civilian scientific community (NSF). These measures would not necessarily reduce the overall cost to the government. However, these costs may be balanced by the nonscientific benefits of the science submarine not considered in our analysis.

Finally, our analysis does not account for the uncertainty of predicting *future* repair and maintenance costs on SSN 686. Historical Navy depot costs for the SSN 637-class submarines show considerable variability between hulls and years, suggesting that is difficult to predict repair activities on a large and complex facility such as a nuclear-powered submarine. From the point of view of the civilian science community, these uncertainties could be addressed through contractual agreements with the Navy and the depot contractors (e.g., NSF could have fixed-price contracts for maintenance activities).

Main Cost Findings

The total cost of operating and maintaining the *L. Mendel Rivers* as a dedicated science submarine could range from roughly $200 million to $300 million over an expected seven years of operation. Approximately $95 million to $125 million would be required for depot overhaul and science conversion, $20 million to $38 million for depot maintenance, $37 million to $55 million for operations including the cost of a Navy crew and consumables, and approximately $60 million for science support. The wide range of potential costs are largely due to different assumptions about whether the submarine could be overhauled and maintained at public or private shipyards, the allocation of overhead, and whether the costs of Navy crew members would be shared between NSF and the Navy. These issues would likely be resolved and the cost made more certain if and when the government begins serious planning for a dedicated science submarine. The average annual cost of the submarine would range from $30 million to $40 million per year. By comparison, current NSF funding for Arctic research, logistics, and facilities support totaled approximately $70 million in FY 2000.

The cost of the submarine is unevenly distributed over time. The initial overhaul and science conversion of the existing vessel constitutes more than a third of the total lifetime costs of the science submarine. Thus, the majority of spending would occur in the first years of the program, and hence there is little flexibility to reduce costs by focusing the science submarine on a few high-priority missions.

The costs of dedicated science submarine are not much smaller than those of a dedicated military submarine (only about a 15 percent to 30 percent reduction), because the costs are largely driven by Navy requirements for safely operating and maintaining the vessel.

Our cost estimates are summarized in Table 4.1, which compares our "high," "medium," and "low" estimates, along with the Navy's cost estimate for a science submarine, from which our cost estimates are based.[2] The bottom row of the table shows the assumptions that are required to achieve the civilian cost savings over the Navy estimate. In this table the assumptions are additive: The medium scenario includes the assumptions for the high estimate, the low estimate includes the assumptions for the high and medium cases. RAND's high cost estimates for the dedicated science submarine differ from the Navy estimates because we have omitted costs associated with military equipment and operations. Our medium cost estimate differs from the high cost because we have assumed an alternative allocation of overhead costs for some maintenance activities. Our low cost estimate assumes that much of the maintenance and overhaul work could be done at private shipyards, which would further reduce costs. Excluding costs for science conversion and maintenance, the high cost estimate for the entire seven-year period is $213 million, $31 million less than

[2]The Navy estimates were presented to the RAND team on August 6, 1999, during a meeting with personnel from the following naval offices: NAVSEA08, NAVSEA92B, PMS392, and N871.

the Navy estimate for continued military operations. The low cost estimate is $147 million, nearly $100 million below the Navy estimate. The specific components of these costs and the assumptions underlying them are explained in the subsections that follow.

As described in detail below, and in Appendices A and B, these cost estimates are based on data obtained from a variety of sources, including the Navy, Electric Boat Company (a shipbuilding contractor), NSF, and the Coast Guard.

Table 4.1. USS *L. Mendel Rivers* Cost Estimates for Overhaul and Seven Years of Operations (FY2000$M)

Cost Category	USN Operations	Science Operations (High)	Science Operations (Medium)	Science Operations (Low)
Onetime Overhaul and Conversion	141	125	125	95
Depot Overhaul	136	120	120	90
Science Conversion	5	5	5	5
Recurring Maintenance	45	38	25	20
Scheduled Major Maintenance (DSRA)	12	10	10	8
Intermediate Maintenance	20	17	7	5
Unscheduled Maintenance	13	11	8	7
Operations	63	55	55	37
Navy Crew	55	47	47	29
Consumables	8	8	8	8
Scientific Support	60	60	60	60
Science Crew	4	4	4	4
Research Support	56	56	56	56
TOTAL COSTS	309	278	265	212
Key Assumptions	Navy estimates of overhaul, maintenance, and operations of a military submarine.	Depot costs can be reduced by 15% by eliminating military systems. Navy crew reduced by 20.	Program pays reduced overhead costs for maintenance.	Depot work in private yards. Navy-NSF cost sharing on crew costs.

The Navy provided us with aggregate estimates of depot repair, normal maintenance (including scheduled and unscheduled work), and personnel costs. These estimates approximated what the Navy would have requested in budget items for operating the *L. Mendel Rivers.* A detailed basis for these estimates was not provided. To place these estimates in perspective, we also examined the Navy's extensive historical record of operation and maintenance costs for all SSN 637-class hulls. Data for this overview came from the VAMOSC (Visibility and Management of Operating and Support Costs) database and SUBMEPP (Submarine Maintenance, Engineering, Planning, and Procurement). We also used independent cost estimates of the science conversion costs provided by Electric Boat Company, a government contractor with substantial experience constructing and maintaining nuclear-powered submarines. Finally, the scientific support cost estimates are derived from data on the costs for icebreaker operations, as reported by the U.S. Coast Guard and in the National Research Council Report, *Arctic Ocean Research and Supporting Facilities* and data on the levels of NSF support for the SCICEX program.

What Are the Components of the Estimated Costs?

There are two broad categories of cost associated with using SSN 686, the *L. Mendel Rivers*, as a dedicated research submarine—the costs of any modifications or conversions, and the costs to operate and maintain the ship. The cost analysis shows that a large fraction of these costs are driven by Navy requirements for submarine operations, including: nuclear submarine maintenance requirements and schedules for SSN 637-class submarines; requirements for the operation and maintenance of a science submarine, as indicated by the SCICEX experience; and ship-manning requirements.

The Navy manuals and memoranda describing nuclear submarine maintenance requirements and schedules for SSN 637-class submarines specify a schedule of maintenance activities that must be performed for all hulls. These requirements are heavily influenced by the principle of "reliability-based maintenance" implemented as part of the SUBSAFE program to insure the safety of nuclear submarines and their crews. One of the operational principles is that the overall safety of the hull depends on the performance of all its engineering systems, and that the failure of specific components could have catastrophic implications.

Lessons from SCICEX suggest that Navy requirements for the operation and maintenance of a science submarine include: a technical crew of at least five individuals responsible for maintaining the science facilities on the submarine; individual investigators who want to collect and analyze data; and new sensors or systems that would be required by the scientific mission.

Ship-manning requirements for SSN 637-class submarines are well defined by Navy regulations. The 1998 assigned crew included 13 officers and 120 enlisted men. In actual practice, this number may vary slightly. To obtain a rough estimate of the cost difference between a military mission and a scientific mission, we obtained the personnel costs associated with the *L. Mendel Rivers* in 1998, its last year of operation, and deleted 20 selected ratings from the crew.

In the following section we first discuss the overhaul, operations, and maintenance costs associated with the operating the submarine according to these Navy requirements. We then discuss the costs of converting the submarine for scientific missions and conducting those missions. Throughout this chapter all costs are expressed in FY 2000 dollars unless otherwise noted.

Operation and Support Costs

During the early phases of this project, the Navy prepared an estimate of the cost to continue operating the *L. Mendel Rivers* to the end of its hull life. The estimate was presented to the RAND study team and a representative of NSF at a meeting in Crystal City, Virginia, on August 6, 1999. This estimate is the starting point for determining the operations and support costs for a dedicated research submarine.

The Navy estimate represents what would be placed in the Navy's budget to continue operating the *L. Mendel Rivers* to the end of its service life. The estimate is presented by fiscal year from FY 2000 through FY 2008 and is in then-year dollars.

The Navy estimate addresses six elements of cost that are relevant to the continued operation of *Rivers*: a depot overhaul (in Navy terms, an "Engineered Overhaul" or EOH), a scheduled major maintenance ("Docking Selected Restricted Availability" or DSRA), annual crew costs ("Military Personnel" or MPN), annual cost for consumable materials and parts ("Operating Tempo" or OPTAR), annual cost for intermediate maintenance (IMA), and annual cost for unscheduled repairs and other maintenance that may or may not require a shipyard (Other/Emergent RA/TA). The first two items are depot-level scheduled maintenance activities and are accomplished in a shipyard.[3]

The Navy estimate is presented in Table 4.2. Note that there are six full years of operations (FY 2002–2007) and two half-years (FY 2001 and FY 2008) according to the Navy schedule.

Table 4.2. *USS L. Mendel Rivers* Life Extension Costs (FY$M)

Cost Category	**FY00**	**FY01**	**FY02**	**FY03**	**FY04**	**FY05**	**FY06**	**FY07**	**FY08**	**Total**
Depot Overhaul	13.8	124.2								138.0
DSRA				0.3	1.9	10.5				12.7
Navy Crew		4.1	8.5	8.8	9.0	9.3	9.6	9.9	5.0	64.2
Consumables		1.2	1.3	1.3	1.3	1.3	1.3	1.3	0.7	9.7
Intermediate Maintenance		3.1	3.2	3.2	3.3	3.3	3.4	3.4	1.8	24.7
Unscheduled Maintenance		1.9	2.0	2.0	2.0	2.1	2.1	2.2	1.1	15.4
Annual Total	13.8	134.5	15.0	15.6	17.5	26.5	16.4	16.8	8.6	265

Before proceeding with any analysis, the estimates in Table 4.2 must be converted to constant dollars. Table 4.3 shows the total costs in FY 2000 dollars. These values are shown in the Navy estimate column of Table 4.1.

[3]The Navy estimate also showed estimates for inactivation and reactor compartment disposal, which we do not include here. These must be accomplished whether the submarine is modified and used for scientific research or not. The Navy will either fund these costs in FY 2000–2001 or in FY 2007–2008, assuming *Rivers* continues operations to the end of its hull life. The costs should not be relevant to NSF's use of the submarine as a research platform.

Table 4.3. USS *L. Mendel Rivers* Life Extension Costs (FY2000$M)

Cost Category	Total
Depot Overhaul	136
DSRA	11.7
Navy Crew	55.3
Consumables	8.4
Intermediate Maintenance	19.7
Unscheduled Maintenance	12.8

The following sections discuss RAND's analysis of and adjustments made to the Navy estimate to arrive at an estimated cost for a dedicated science submarine. We present three estimates: the first, labeled "high," embodies verbal estimates from the Navy on the potential cost savings in overhaul and maintenance of submarine without "warfighting" capabilities. The second, labeled "medium," calculates maintenance overhead costs based on the VAMOSC data rather than the Navy estimates. The third estimate, labeled "low," moves most overhaul and maintenance to a private shipyard such as Electric Boat or Newport News Shipbuilding and shares Navy crew costs between the Navy and NSF.

Depot Overhaul

SSN 637-class submarines are managed according to the Engineered Operating Cycle (EOC) maintenance strategy.[4] The operating cycle is 84 months following a regular or refueling overhaul. During this 84-month cycle there are three operating intervals of 28 months with a two-month DSRA between each operating interval. At the end of the 84-month cycle, the submarine undergoes another overhaul unless it is being retired, in which case it undergoes an inactivation.[5] The overhaul period is approximately 18 months. All these

[4]See *Submarine Engineered Operating Cycle (SEOC) Program,* OPNAV Instruction 3120.33B, CH-3, September 25, 1998; *Notional Intervals, Durations, Maintenance Cycles, and Repair Mandays for Depot Maintenance Availabilities of U.S. Navy Ships,* OPNAV Notice 4700, Ser N433F/6U594506, March 1, 1996; and, *Notional Intervals, Durations, and Repair Man-days for Depot Level Availabilities of United States Navy Ships,* OPNAV Notice 4700, Ser N433G/2U599597, December 2, 1992. Parche (SSN 683) does not follow the EOC maintenance strategy.

[5]SSN 637-class hull life is 33 years. Submarines reaching this are retired from service. They may be retired earlier for various reasons. All except four 637-class submarines were decommissioned before the start of FY 2000, and two of those four started their inactivations on September 1, 1999 (William

intervals are nominal and can be adjusted depending on fleet needs, submarine material condition and reactor core life.

L. Mendel Rivers will reach the end of her hull life in February 2008 and her core life is projected to May 2008. The end of her current operating cycle was January 2, 2001. If she is to return to service as a scientific research vessel, she must have an overhaul.

The Navy estimate for the cost of the overhaul is $138 million in then-year dollars. Ten percent of this would be appropriated in FY 2000 and the other 90 percent in FY 2001. The submarine would be in the shipyard from December 2001 to May 2002. The $136 million (FY2000$) estimate is based on 200,000 man-days of work in the shipyard at an average cost of $600 per man-day, plus 15 percent to cover materials. The Navy compared the man-day value to a historical average of approximately 350,000 man-days.[6] Hence, the estimate is a significant reduction compared to 637-class historical overhaul costs. The Navy believes that 200,000 man-days is the minimum needed to prepare and recertify the ship for an additional normal Navy operating cycle. A large part of the reduction derives from changes in the maintenance plan and philosophy, drawing on experience from the 688-class. The Navy estimates that the warfighting capabilities of the submarine account for approximately 15 percent of the availability cost, which suggests that if the *L. Mendel Rivers* is prepared strictly for scientific operations it would require 170,000 man-days and cost in the neighborhood of $120 million (FY2000$) for the overhaul.[7] This excludes the cost of any modifications for scientific equipment, science crew accommodations, etc. We use this figure for our high and medium cost estimates.

It has been suggested that the overhaul could be accomplished at one of the qualified private shipyards[8] and that the modifications for scientific use could be made at the same time. Studies of labor rates at the private yards versus the public (Navy) shipyards indicate that the private yards' rates are one-quarter to one-third less than the public yards' rates. Assuming a 25 percent reduction would bring (the non-conversion portion of) the overhaul down to approximately $90 million (FY2000$). We use this value for our low cost

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H. Bates, SSN 680) and October 1, 1999 (Hawkbill, SSN 666). Only Parche (SSN 683) and the *L. Mendel Rivers* (SSN 686) remain in active service in FY 2000. Retirement ages for decommissioned submarines (age from commissioning to decommissioning) range from 18.9 years (SSN 687, Richard B. Russell) to 28.8 years (SSN 674, Trepang).

[6] Analysis of data for thirteen 637-class refueling overhauls shows 35,400 man-days and 12.5 percent additional cost for material. For 15 regular (non-refueling) overhauls, the corresponding values are 329,000 man-days and 14.3 percent for material costs.

[7] Most of the information in this paragraph was communicated verbally at the August 6 meeting.

[8] General Dynamics Electric Boat and Newport News Shipbuilding are the two current, private shipyards that construct nuclear-powered submarines.

estimate. It is important to note, however, that these estimates represent costs to the nation of a dedicated scientific submarine. It is possible that the Navy could have underutilized personnel in its yards. Under such conditions the incremental costs for such a submarine attributable to NSF could be less than this low estimate if the work was performed in these public yards. An evaluation of this issue was beyond the scope of this study.

Scheduled Major Maintenance (Docking Selected Restricted Availability [DSRA])

The Navy estimate of $11.7 million (FY2000$) for the DSRA represents a very significant improvement over the historical norm for 637-class submarines. As mentioned in the first paragraph of the Overhaul section above, the EOC maintenance strategy requires *two* DSRAs between overhauls (or between the last overhaul and inactivation). Based on experience with the 688-class submarines, the Navy projects that the two DSRAs can be replaced by a single DSRA midway through the operating cycle. Of course, the work content and the cost of the single DSRA are greater than one of the two DSRAs. The Navy provided RAND with actual costs for eighty 637-class DSRAs, all conducted under the EOC strategy. These DSRAs average $9.6 million (FY2000$). Two of them would cost $19.2 million; thus, the Navy projects a savings of approximately 40 percent relative to the EOC.

For science operations, we again assume elimination of the combat systems maintenance (high cost estimate) and use the private shipyard man-day rate benefit (low cost estimate). Reducing by 15 percent for the combat systems yields $10.2 million (FY2000$), which we use for our high and medium cost estimates. A further 25 percent reduction for the private yard rate yields a total of $7.7 million (FY2000$), which we use for our low cost estimate.

Navy Personnel

This and the next three categories were not discussed at the August 6, 1999 meeting with the Navy.[9]

A principal concept in using the *L. Mendel Rivers* as a dedicated science platform is that the Navy crew would be reduced to allow room for science personnel and equipment on board. To develop an estimate for the reduced Navy

[9]Subsequent telephone conversations provided some definitions regarding the OPTAR, IMA, and RA/TA estimates. The MPN estimate was simply described as a standard budget figure.

crew costs, we obtained detailed crew composition information and identified specific personnel to remove for science operations. We also developed an estimate of complete Navy crew costs that matches the value presented in the Navy's estimate.

The *L. Mendel Rivers'* crew composition data were obtained from the FORMIS (Forces Readiness and Manpower Information System) database.[10] FORMIS provides three crew compositions for three fiscal years. The crew compositions are the actual crew assigned, the authorized crew, and the required crew. For the *L. Mendel Rivers,* the authorized and assigned crews are identical. Appendix A shows the authorized crew, the actual crew for FY 1998 (the most recent available at the time) and a proposed science crew. We used the authorized crew to obtain an estimate consistent with the Navy estimate, assuming it would use that crew for budgeting purposes. To develop the science crew, we removed specific personnel from the FY 1998 crew. The reduction is 20 below the actual crew and 25 less than the authorized crew.

Crew cost estimates were determined using the FY 2000 pay rates and factors presented in the Justification of Estimates from the Navy FY 2000/2001 Budget.[11] Results for the FY 1998 Authorized crew and the proposed science crew are shown in Table 4.4. Blank cells have zero cost. Cells with a 0.00 entry have costs less than $10,000 per year. The annual cost for the authorized crew is $7.97 million (FY2000$) and for the science crew it is $6.65 million (FY2000$), which is a reduction of 17 percent. Over seven years this yields $47 million, which we use for our high and medium cost estimates.

Retaining the *L. Mendel Rivers* in service may have benefits for the Navy, even if it is converted to a "non-combat" configuration. If this is the case, then it could be argued that it would be fair for NSF and the Navy to share some of the costs. The most logical area for such sharing would likely be in crew costs. The Navy crew remains in the Navy and would obtain experience and training with some positive value to the military branch. Also, the Navy could benefit directly from at least some of the scientific research. This is something that would have to be worked out between the Navy and NSF. Perhaps an agreement based on the various cost categories that constitute the budget cost of Navy personnel could be agreed to. To illustrate this, consider the Basic Pay, Retired Pay Accrual, and Social Security/Medicare categories. These correspond to the categories that NSF would be paying the science crew. If the

[10]The FORMIS database can be accessed on the Internet at http://www.dmdc.osd.mil/formis. This is a secure site and requires ".mil" access and a user ID and password.
[11]Department of the Navy FY 2000/2001 Biennial Budget Estimates, Justification of Estimates, February 1999.

other categories were covered by the Navy, then the NSF cost for the Navy crew would be reduced to $4.08 million (FY2000$) per year, or $29 million over seven years. We will carry this number in our "low" cost estimate.

Table 4.4. Annual Navy Personnel Costs—Military Crew versus Science Crew

Cost Category	98 Authorized Crew			Science Crew		
	off	enl	total	off	enl	total
Basic Pay	0.57	2.67	3.25	0.38	2.31	2.68
Retired Pay Accrual	0.19	0.85	1.04	0.12	0.73	0.86
Submarine Duty	0.07	0.27	0.35	0.04	0.25	0.29
Career Sea	0.03	0.28	0.31	0.02	0.26	0.28
Diving Duty		0	0		0	0
Imminent Danger		0.22	0.22		0.19	0.19
Nuclear Officer	0.08		0.08	0.08		0.08
Reenlistment Bonus		0.07	0.07		0.06	0.06
Basic Allowance for Housing	0.15	0.8	0.95	0.1	0.71	0.8
Basic Subsistence	0.03	0.21	0.24	0.02	0.18	0.19
Subsistence in Kind		0.3	0.3		0.25	0.25
Clothing Allowance	0	0.07	0.07	0	0.06	0.06
On Board more than 30 Days	0.02	0.15	0.17	0.01	0.12	0.14
Terminal Leave	0	0.02	0.02	0	0.02	0.02
Permanent Change of Station	0.05	0.17	0.22	0.03	0.14	0.18
Other	0	0.03	0.03	0	0.02	0.02
Social Security/Medicare	0.09	0.56	0.65	0.06	0.48	0.54
Total	1.29	6.69	7.97	0.87	5.78	6.65
Crew Size	14	124	138	9	104	113

Consumables

In the current context, consumables (in Navy terms, the "Operational Target" or OPTAR) include services and materials consumed or used by the ship in operations and in any maintenance other than intermediate or depot maintenance.

The Navy VAMOSC (Visibility and Management of Operating and Support Cost) system[12] provides an independent source of data for this, and the next two categories. For this study, RAND obtained the 637-class individual ship, annual, VAMOSC data for FY 1984 through FY 1997.[13] This amounts to 440 "submarine-years" of data. We restricted our analysis to only those submarines that were active throughout the time period and that followed the EOC maintenance strategy. This reduced our sample to 30 submarines for nine years, for a total of 270 "submarine years." The average annual cost of consumable materials, per ship, is $1.35 million (FY2000$). The seven-year total is $9.5 million, which is greater than the estimate provided by the Navy for extension of the *L. Mendel Rivers* operations. The Navy estimate is based on the most recent three years of data for 637-class submarines. We have no basis for reducing either of these estimates as a result of not operating the combat systems or taking advantage of private shipyard labor rates. Consequently, we use for all our cost estimates the Navy provided estimate of $8.4 million for the seven-year total cost.

Intermediate Maintenance

This category covers the cost of material and labor expended by a tender, repair ship, or equivalent ashore or afloat intermediate maintenance activity for any repairs other than scheduled depot maintenance (e.g., depot overhaul and DSRA) and unscheduled maintenance.

Again, we turn to the VAMOSC data. The average annual cost of intermediate maintenance, per ship, is $710,000 (FY2000$), for a seven-year total of $5 million. This amount does not include any overhead costs for the intermediate maintenance, which at least partially explains why the amount is so much lower than the Navy-provided estimate, which includes overhead (for a total of $19.7 million over seven years). The Navy's estimate is based on the most recent three years and assumes the work is done at the homeport yard (Norfolk for the *L. Mendel Rivers*). Considering the number of active 637-class submarines has been rapidly dropping in the past few years and that it is likely the overhead facilities at Norfolk supporting these submarines have not been reduced in proportion to the decrease in the number of active submarines, the overhead allocation per submarine in the Navy's estimate may be

[12]VAMOSC is maintained by the Naval Center for Cost Analysis (NCCA). Information about VAMOSC can be found on the NCCA Web site at http://www.ncca.navy.mil.

[13]For this time period, the average 637-class submarine age is 19.3 years, and the maximum and minimum are 27.9 and 8.9 years, respectively. In FY 1997, the *L. Mendel Rivers* was 22.4 years old. All ages are measured from the commissioning date.

exceedingly high.[14] We were not able to investigate this during the course of the project.

The issue here is whether NSF should cover the costs of facilities at Norfolk Naval Shipyard, especially if as a dedicated research submarine, *Rivers* is home-ported at one of the private yards (Electric Boat or Newport News). For our estimates here, we take the Navy estimate reduced by 15 percent (to $17 million) to reflect no maintenance of the combat systems, for the "high cost" value.

To arrive at the medium and low cost estimates, we start from the VAMOSC data rather than the Navy estimates. To correct for the absence of overhead costs in the VAMOSC data, we increase the $5 million figure by 32 percent, which is the ratio of overhead to labor plus material costs for depot overhaul at a public shipyard as given in VAMOSC for 637-class submarines. Thus, our medium cost estimate for IMA cost is $6.6 million (FY2000$).

We further reduce this by 25 percent to reflect the private shipyard rate advantage, for our "low cost" estimate of $5 million.[15]

Unscheduled Repairs

This category includes nonscheduled depot level repairs requiring the ship to be in a shipyard (in Navy terms, "Restricted Availability"), and rendering it incapable of performing its mission; and also nonscheduled depot-level repairs that do not require the ship to be in a shipyard and do not interfere with the ship's ability to perform its mission (in Navy terms, "Technical Availability"). The common thread here is that both types of availability involve unscheduled maintenance and cannot be accomplished by the ship's crew or an intermediate maintenance activity.

From VAMOSC, the average annual cost of unscheduled repairs, per ship, is $1.04 million (FY2000$). VAMOSC also has an Other Depot Maintenance category, which for submarines contains costs for depot-level component rework and maintenance planning. The average annual cost per ship is $260,000 (FY2000$). Combining these two costs yields a seven-year total of $9.1 million,

[14]If the overhead in the $19.7 million figure is at 32 percent, then the labor plus material cost is $14.9 million or nearly three times the historical VAMOSC value. It seems more likely that the overhead is high.

[15]This area should be investigated more thoroughly by NSF if there is a decision to proceed with conversion of *Rivers* for science operations, especially if the submarine is homeported at a private yard.

as compared to the Navy estimate of $12.8 million. We reduce this value by 15 percent to give our high cost estimate of $11 million.

Again, the Navy estimate is based on the three most recent years and may be biased upward. We use the $9.1 million from the VAMOSC data "unscheduled repairs" cost category. Because this includes repairs of combat systems, we reduce our estimate by 15 percent as with the categories above to give a medium cost estimate of $8 million. Because the repairs covered by this category are unscheduled, it does not seem reasonable to assume that they can all be accomplished at a private shipyard. Some repairs will be urgent while others may be postponed until the submarine returns to its homeport. For our low cost estimate, we assume half of the unscheduled repairs will be performed in a private shipyard, corresponding to $6.8 million (FY2000$).

Science-Related Costs

Science Conversion Costs

The Navy did not provide estimates of the onetime cost of preparing the *L. Mendel Rivers* to conduct scientific missions. RAND estimates that the cost of these modifications, shown in detail on the following pages, is a onetime expenditure of $5 million.

Although the costs of converting the *L. Mendel Rivers* for scientific use would be a small fraction (approximately 2 percent) of the total costs, it is nonetheless useful to examine the basis of these costs in some detail. As opposed to the other costs of the science submarine, these modifications are new and unique to this mission.

RAND asked Electric Boat to provide a notional design of the modifications necessary to improve SSN 686 as a dedicated scientific platform. These modifications would focus on the torpedo room, half of which would be converted into laboratory space. The modifications would include installing laboratory equipment for analysis, universal hull mounts for external instrumentation, a flow-through manifold for water sampling, a head for the scientific party; and developing a computer work room and internal data network.

These modifications would be made consistent with all Navy SUBSAFE Certifications. The scientific modifications would cause no change in the submarine's operating characteristics, such as bare hull ship speed and operating depth. Any systems and equipment not needed to meet scientific mission requirements would be inactivated in place.

We did not consider all the possible modifications for a science submarine. For instance, we did not include equipment for vertical water sampling or handling capabilities, other than the torpedo tubes for launching autonomous underwater vehicles (AUV/ROV).

While the modifications we assume in this analysis are removable, there is no need to reinstall them for each mission. Additional scientific modifications beyond those considered here could be installed during regular repair periods between missions.

Figure 4.1 shows Electric Boat's notional layout of the forward torpedo room of the *L. Mendel Rivers* as modified for scientific use. It shows the port side of the torpedo room, including tubes and handling equipment, converted to support the scientific mission. The starboard side of the room is left unchanged.

This design provides berths for 15 scientists, and eliminates 22 crew berths during science missions. The design adds one head near the science space, four paperwork and storage stations in the torpedo room, a wet lab in the torpedo room, additional power in the laboratory space, and chill and frozen storage.

Not shown in this figure, but included in the cost estimates, are the addition of universal DOLPHIN (AGSS 555) external equipment mounts with standard electrical penetrators forward above ship's surface waterline, the installation of a Seafloor Characterization and Mapping Pod (SCAMP), and a through-hull water sampling manifold in the lab.

Figure 4.2 provides further detail: a close-up view of the forward torpedo room's port side as converted for scientific use.

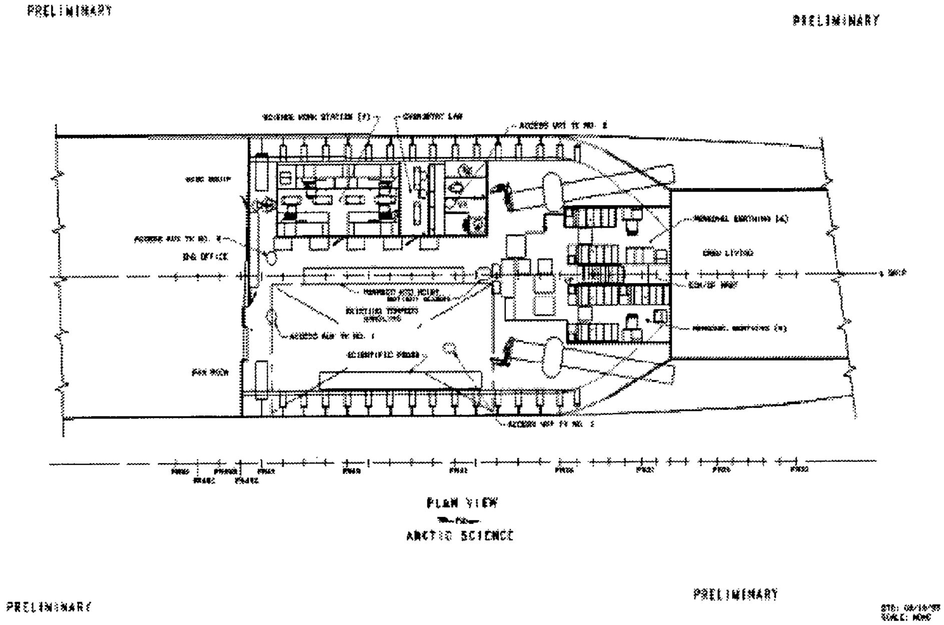

Figure 4.1 Notional Design of Science Modifications

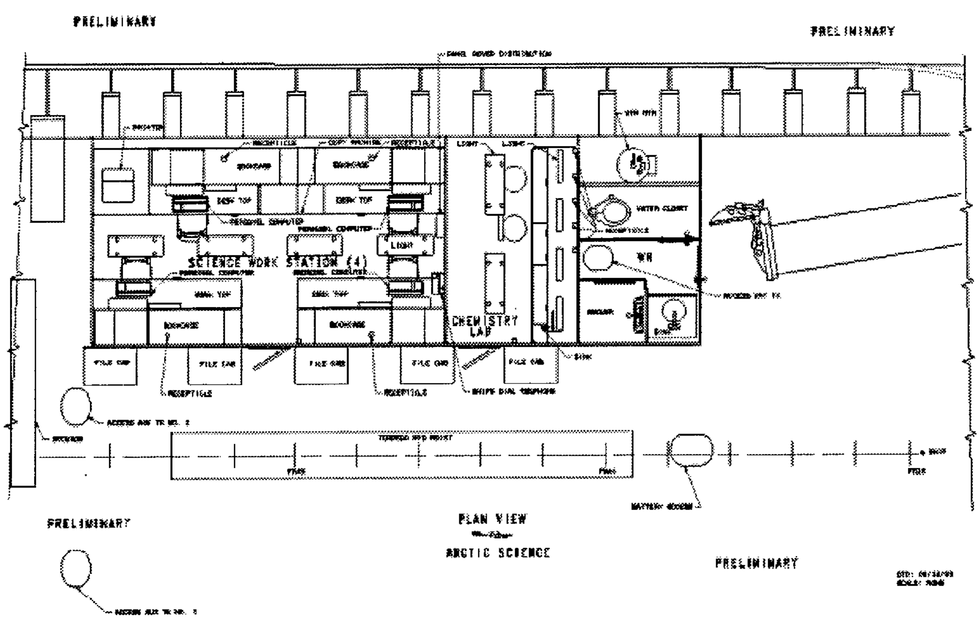

Figure 4.2 Notional Design Detail of Modifications for Scientific Activities

Science Support Costs

In addition to the conversion costs, there are costs to support the scientific mission. Separate from the onetime installation and conversion activities during the depot overhaul, the scientific support costs can be viewed as ongoing operational expenditures. We assume that these costs are driven by two major components:

- Support for a submarine science crew
- Support for individual investigators who want to collect and/or analyze data, including new sensors or systems that are required for the scientific mission.

The scientific support costs involve a crew of science technicians and funds for individual research projects and new sensors. Based on experience from the SCICEX cruises, we assume a crew of five technicians with an annual salary of $100,000 (including all benefits and indirect costs). With these assumptions, the submarine science crew would cost $250,000 to $500,000 per year, depending on whether these crew costs were attributed to the dedicated science submarine for the entire year of only the period when it was at sea. Consistent with our assumptions about the allocation of Navy crew costs, we use the full annual cost for our high and medium cost estimates and the days-at-sea estimate for our low cost estimate.

Based on the NSF support for SCICEX missions between 1993 and the present, we estimate that each project on a science submarine would require $250,000 of support; there would be 10 projects per cruise and 3 cruises per year. We anticipate that these funds would allow a modest level of sensor development for new submarine measurements and experiments. With these assumptions, the total scientific support costs would be $8 million per year.

This level of support is comparable to the average award level for the competitive projects from the Office of Polar Programs (OPP) in FY 1999. These awards include investigator support and equipment costs for the entire Polar Research Program in the Arctic and Antarctic. More important, it excludes logistical support. We can refine this number by considering the historical NSF support for the SCICEX missions. All told, more than 45 projects between 1993 and the present amounts to more than $9.19 million (in current-year dollars), corresponding to an average award of $204,000. This value is slightly less than the OPP average in 1999 and it may be influenced by the large increase in funding for this program over the past five years (see Table 4.5). The SCICEX support projects range from support for individual investigators for specific data analysis to the design and installation of specialized equipment (e.g., the SCAMP system).

Comparison with Current NSF Expenditures

To benchmark the operation, maintenance, and science support costs for a research submarine, we compared the submarine cost estimates to current federal budgets in related areas of research and science. For the most part, this analysis focused on Arctic research supported by NSF. The rationale for this approach is that the largest fraction of the submarine benefits will be realized in the Arctic, where NSF is the largest supporter of research activities.

The purpose of this analysis is to put the proposed submarine expenditures in the context of current U.S. research budgets. In essence, we ask: How would the science submarine's cost compare to the budgets in comparable fields of science? The submarine would augment existing research activities. Therefore, we want to compare the cost of submarine activities to the cost of those existing research activities. Overall, total annual NSF expenditures in the Arctic were approximately $70 million. In FY 1999, annual support for the entire federal oceanographic research fleet was approximately $60 million.

As articulated by the Arctic Research Commission, U.S. funding priorities in the Arctic encompass basic and applied research activities, education initiatives for Arctic residents, and support for research infrastructure and logistics. The topic areas for our analysis overlap three of the Commission's recommendations for basic research: studies of the Bering Sea, studies of Arctic climate change, and Arctic Ocean research. The fourth recommendation, environmental health of Arctic residents, would not be impacted by submarine data. Table 4.5 details the full range of Arctic research expenditures by U.S. government agencies addressed to the priorities of the Arctic Research Commission.

Table 4.5 Arctic Research Budgets of Federal Agencies

AGENCY	FY96 Actual	FY 97 Planned	FY 98 Proposed
DoD	30.5	24.5	13.1
DOI	32.7	27.9	27.3
NSF	46.2	47.8	50
NASA	38	38.2	33.7
DOC	13.7	12.8	11.5
DOE	4.2	4.2	4.2
DHHS	6.4	6.5	6.5
Smithsonian	0.5	0.5	0.5
DOT	6.9	6.3	6.3
EPA	0.8	0.5	0.5
USDA	2.8	2.8	2.8
STATE	0.6	0.5	0.5
TOTAL	182.7	172	156.2

Source: U.S. Arctic Research Commission
Note: Totals do not add due to rounding.

Most NSF research in the Arctic is supported by the U.S. Polar Research Program, which supports research in both the Antarctic and Arctic. The total budget for Office of Polar Programs in FY 2000 was $188 million, as shown in Table 4.6. An additional $62.6 million was budgeted for logistical support in the Antarctic to the Department of Defense. The majority of the Polar Research Program supports Antarctic research and operations; annual NSF expenditures in the Arctic are approximately 28 percent of the total budget ($70 million in FY 2000).

Table 4.6 FY2000 Budget for Polar Research ($M)

U.S. Antarctic Logistic Support (to DoD)	62.6
U.S. Polar Research Programs	188.0
Arctic Research (supports SCICEX)	(49.5)
Antarctic Research	(30.7)
Operations and Science Support	(106)
TOTAL	250.6

Note: Totals due not add due to rounding.

While the Arctic component of this program is less than 25 percent of the budget, it is the fastest growing line item in the program, and it is the subject of continuing congressional interest during the appropriations process. According the NSF budget submission, the Polar Research Program supports 70 percent of NSF's university-based research in the Arctic. The NSF budget notes that this line item supports a wide range of research platforms in the Arctic. That is, current funds are not concentrated in a single large facility, comparable to a submarine, but are dispersed across many efforts that include icebreakers, other oceanographic vessels, ice camps, and other research platforms, as described in Chapter 2.

Compared with it support for Arctic research, NSF support for oceanography is significantly larger, and NSF is only one of several federal agencies that supports oceanographic research. These include the U.S. Naval Oceanographic Office (NAVO), Office of Naval Research (ONR), and NOAA. Table 4.7 details the NSF support for oceanography in the ice-free oceans. At the top level, the program budget is $58.3 million. With the Ocean Sciences budget, NSF provides $42.3 million to support the Academic Research Fleet for oceanographic research. In FY 1999, these NSF funds supported 325 projects carried out by 2,500 scientists on 28 ships where NSF users accounted for 75 percent of the total use. Considering the entire U.S. fleet of research vessels, NSF accounted for approximately 50 percent of the total ship days in FY 1999.

Table 4.7 Support for Entire Federal Academic Research Fleet (FY1999) Operations and Maintenance ($M)

NSF	42.3
ONR	5.9
NAVO	7.5
NOAA	2.6
TOTAL	58.3

Chapter 5. Conclusions

In this study we have estimated the costs and benefits of using a dedicated science submarine to conduct unclassified scientific research throughout the world's oceans, primarily in the Arctic region. As a concrete example, we have studied converting and operating a SSN 637-class submarine, the *L. Mendel Rivers* (SSN 686), as a dedicated science platform over a seven-year maintenance cycle. We assessed the unique contributions the *Rivers* could make to high-priority national scientific goals and estimated the costs of those contributions.

Scientific Benefits

A dedicated science submarine could provide a wide variety of scientific benefits. In this study we focus on the contributions such a submarine could make to addressing high-level scientific objectives defined by the scientific community in four priority research areas. These areas are: Geologic and Geophysical Exploration of the Arctic Basin, Arctic Climate Change, the Dynamics of the Bering Sea Ecosystem, and general Oceanographic Studies in the Ice-Free Oceans. In these areas, a submarine's ability to move quickly, quietly, and easily to almost any location in any season or weather can prove particularly advantageous. This focus on contributions to high-level scientific objectives is consistent with the methodology used by the National Science Foundation to evaluate investments in other large research facilities.

There is an existing, broad-ranging program of Arctic research to which the measurements from a dedicated science submarine would contribute. We thus focus on the unique contributions a submarine could make to these four high-priority research areas, that is, the benefits gained by adding a submarine to the existing portfolio of research platforms for the Arctic, including surface ships, icebreakers, satellites, autonomous underwater vehicles, ice camps, airplanes, remote buoys, and instrumentation for acoustic propagation measurements.

We find that a dedicated science submarine would contribute most significantly to the priority research areas of Geologic and Geophysical Exploration of the

Arctic Basin and Arctic Climate Change. Central to these contributions is the submarine's ability to collect survey data in ice-covered seas.

A submarine is unmatched in its capability to collect large amounts of bathymetric or hydrographic data over the Arctic Basin, especially in the winter. A submarine also has unique capabilities to collect controlled seismic refraction and reflection surveys. Such data directly support the scientific objective of filling long-standing knowledge gaps regarding the Arctic Ocean basin.

A dedicated science submarine could also make unique contributions to understanding the variability of the Arctic climate system and its relation to global climate change. For climate change research, the most important feature of the submarine is the capability to collect data over broad areas of the Arctic Basin at all times of year. Of particular importance are hydrographic measurements in the upper ocean (temperature/salinity profiles), detailed mapping of ice draft and structure, and high-resolution bathymetric surveys.

To a lesser extent, the science submarine could also uniquely contribute to the priority research areas of Dynamics of the Bering Sea Ecosystem, and general Oceanographic Studies in the Ice-Free Oceans. In the Bering Sea the submarine has a unique capability to make hydrographic and ice-draft measurements under the ice and to monitor biological features, such as water sampling from specific oceanographic features and mapping fish and zooplankton populations. However, the extent of these benefits is limited by water in much of the Bering Sea that is insufficiently deep for safe submarine operations (40 percent of the Bering Sea is less than 100 m deep).

In the ice-free oceans, the submarine has fewer unique capabilities relative to surface ships, satellites, and drifting buoys. Without the limitations of an ice cover, ships have greater navigational capabilities, satellites can image a range of ocean properties over vast areas, and buoys can drift great distances. Under these circumstances, the submarine's primary strength centers on data gathering in remote regions, rough seas, and bad weather.

Our analysis focuses on the benefits of a dedicated science submarine in relation to the proven, current capabilities of other research platforms. We note, however, that the technology associated with autonomous underwater vehicles is improving rapidly and could plausibly lead to platforms that equal or surpass many of the submarine's unique measurement capabilities over the course of roughly a decade.

Costs

The total cost of operating and maintaining the *L. Mendel Rivers* as a dedicated science submarine could range from roughly $200 million to $300 million over an expected seven years of operation. Approximately $95 million to $125 million would be required for depot overhaul and science conversion, $20 million to $37 for depot maintenance, $38 million to $53 million for operations including the cost of a Navy crew and consumables, and approximately $60 million for science support. The wide variations in potential costs are due in large part to different assumptions about whether the submarine could be overhauled and maintained at public or private shipyards, whether overhead costs would be shared between the Navy and NSF, and whether the costs of Navy crew members would be allocated to the dedicated science submarine when it was not at sea. These issues would likely be resolved and the cost made clearer if and when the government begins serious planning for a dedicated science submarine. The average annual cost of the submarine would range from $30 million to $40 million per year. By comparison, current NSF funding for Arctic research, logistics, and facilities support totaled approximately $70 million in FY 2000.

The cost of the submarine is unevenly distributed over time. The initial overhaul and science conversion of the existing vessel account for more than a third of the total lifetime costs of the science submarine. Thus in any scenario, the majority of spending would occur in the first years of the program, and hence there is little flexibility to reduce costs by focusing the dedicated science submarine on a few high-priority missions.

Assessment

A dedicated science submarine could make unique and important contributions to the priority research areas of Geologic and Geophysical Exploration of the Arctic Basin and Arctic Climate Change. It could make unique, important, but relatively lesser contributions to the priority research areas of Bering Sea Ecosystem, and general Oceanographic Studies in the Ice-Free Oceans. Maintaining and operating a science submarine could cost $200 million to $300 million over seven years of operations. Many uncertainties remain over the extent of these benefits and costs. For instance, the submarine could have non-scientific benefits not considered in this study; or technological advances could produce autonomous underwater vehicles that in a decade or more could obtain some of the measurements currently available only from a dedicated science submarine. Nonetheless, this report lays a foundation for decisionmaking on the deployment of such a research platform. Specifically we identify the priority research areas that would benefit most from the unique capabilities of a dedicated science submarine. Policymakers can assess the importance of these benefits in light of the costs we have identified.

Appendix A: Proposed Crew for Dedicated Science Submarine

Tables A1 and A2 present the Authorized, Assigned (for FY 1998) and the proposed Science Crews for the *L. Mendel Rivers*. The assigned crew has a different mix of ratings than the authorized crew, with many ratings lower than those on the authorized list. This is common across most ships in the Navy. Our proposed science crew was developed by removing 20 ratings from the assigned crew to accommodate the scientific crew and modifications.

Table A1 *L. Mendel Rivers* Crew Composition—Officer Personnel

Grade	Grade Description	NOBC	Description	Authorized	1998 Assigned	Science Crew
O01	Ensign	1918	General Supply Off	0	1	0
O01	Ensign	7251	Radiological Ctl. Off	1	0	0
O01	Ensign	9242	First Lieutenant, Afloat	1	0	0
O01	Ensign	9394	Ship's Reactor Ctl. Assistant	1	0	0
O02	Lieutenant Junior Grade	7251	Radiological Ctl. Off	0	1	1
O02	Lieutenant Junior Grade	9250	Division Off, Wpns Dept (General)	1	0	0
O02	Lieutenant Junior Grade	9372	Ship's Engineer Off, Nuclear (Main Propulsion)	0	2	2
O02	Lieutenant Junior Grade	9373	Ship's Engineer Off, Nuclear (Damage Ctl.)	0	1	1
O02	Lieutenant Junior Grade	9374	Ship's Engineer Off, Nuclear (Electrical)	1	0	0
O02	Lieutenant Junior Grade	9582	Comm Off, Afloat	1	2	1
O03	Lieutenant	1918	General Supply Off	1	0	0
O03	Lieutenant	9258	Wpns Off (General)	1	0	0
O03	Lieutenant	9274	Opns Off, Afloat (General)	0	1	0
O03	Lieutenant	9371	Ship's Engineer Off, Nuclear (General)	0	1	1
O03	Lieutenant	9372	Ship's Engineer Off, Nuclear (Main Propulsion)	1	0	0
O03	Lieutenant	9373	Ship's Engineer Off, Nuclear (Damage Ctl.)	1	0	0
O03	Lieutenant	9394	Ship's Reactor Ctl. Assistant	0	1	1
O04	Lieutenant Commander	9228	Executive Off, AFLT	1	1	1
O04	Lieutenant Commander	9258	Wpns Off (General)	0	1	0
O04	Lieutenant Commander	9274	Opns Off, Afloat (General)	1	0	0
O04	Lieutenant Commander	9371	Ship's Engineer Off, Nuclear (General)	1	0	0
O05	Commander	9235	Cmding Off, Afloat (Cmder)	1	1	1
Total				14	13	9

Table A2 USS *L. Mendel Rivers* Crew Composition—Enlisted Personnel

Grade	Grade Description	Rating	Rating Description	Author-ized	1998 Assigned	Science Crew
E01	Seaman Recruit	FR	Fireman Recruit	0	1	0
E01	Seaman Recruit	SR	Seaman Recruit	0	2	2
E01	Seaman Recruit	STS	Sonar Tech (Submarine)	0	1	0
E02	Seaman Apprentice	ET	Electronics Tech	0	3	1
E02	Seaman Apprentice	MM	Machinists Mate	0	2	2
E02	Seaman Apprentice	MS	Mess Management Specialist	0	1	1
E02	Seaman Apprentice	SA	Seaman Apprentice	0	1	0
E02	Seaman Apprentice	SK	Storekeeper	0	1	1
E02	Seaman Apprentice	STS	Sonar Tech (Submarine)	0	2	1
E02	Seaman Apprentice	YN	Yeoman	0	1	0
E03	Seaman	ET	Electronics Tech	1	2	1
E03	Seaman	MM	Machinists Mate	3	2	2
E03	Seaman	MS	Mess Management Specialist	1	0	0
E03	Seaman	SK	Storekeeper	1	0	0
E03	Seaman	SN	Seaman	5	2	2
E03	Seaman	STS	Sonar Tech (Submarine)	0	1	0
E04	Petty Officer 3rd Class	EM	Electricians Mate	2	0	0
E04	Petty Officer 3rd Class	ET	Electronics Tech	11	3	3
E04	Petty Officer 3rd Class	FT	Fire Control Tech	3	3	1
E04	Petty Officer 3rd Class	MM	Machinists Mate	10	6	6
E04	Petty Officer 3rd Class	MS	Mess Management Specialist	2	2	2
E04	Petty Officer 3rd Class	SK	Storekeeper	0	1	1
E04	Petty Officer 3rd Class	STS	Sonar Tech (Submarine)	9	5	4
E04	Petty Officer 3rd Class	YN	Yeoman	1	1	0
E05	Petty Officer 2nd Class	EM	Electricians Mate	5	7	7
E05	Petty Officer 2nd Class	ET	Electronics Tech	9	5	4
E05	Petty Officer 2nd Class	FT	Fire Control Tech	1	0	0
E05	Petty Officer 2nd Class	MM	Machinists Mate	14	13	13
E05	Petty Officer 2nd Class	MS	Mess Management Specialist	2	1	1
E05	Petty Officer 2nd Class	SK	Storekeeper	1	0	0
E05	Petty Officer 2nd Class	STS	Sonar Tech (Submarine)	4	2	2
E05	Petty Officer 2nd Class	YN	Yeoman	1	0	0
E06	Petty Officer 1st Class	EM	Electricians Mate	3	3	3
E06	Petty Officer 1st Class	ET	Electronics Tech	6	10	10

Grade	Grade Description	Rating	Rating Description	Author-ized	1998 Assigned	Science Crew
E06	Petty Officer 1st Class	FT	Fire Control Tech	1	2	1
E06	Petty Officer 1st Class	HM	Hospital Corpsman	0	1	1
E06	Petty Officer 1st Class	MM	Machinists Mate	6	10	10
E06	Petty Officer 1st Class	MS	Mess Management Specialist	1	2	2
E06	Petty Officer 1st Class	SK	Storekeeper	0	1	1
E06	Petty Officer 1st Class	STS	Sonar Tech (Submarine)	2	3	3
E06	Petty Officer 1st Class	YN	Yeoman	0	1	1
E07	Chief Petty Officer	EM	Electricians Mate	1	1	1
E07	Chief Petty Officer	ET	Electronics Tech	4	5	5
E07	Chief Petty Officer	FT	Fire Control Tech	1	1	0
E07	Chief Petty Officer	HM	Hospital Corpsman	1	0	0
E07	Chief Petty Officer	MM	Machinists Mate	4	2	2
E07	Chief Petty Officer	MS	Mess Management Specialist	1	1	1
E07	Chief Petty Officer	SK	Storekeeper	1	2	2
E07	Chief Petty Officer	STS	Sonar Tech (Submarine)	0	1	1
E07	Chief Petty Officer	YN	Yeoman	1	0	0
E08	Senior Petty Officer	ET	Electronics Tech	1	0	0
E08	Senior Petty Officer	MM	Machinists Mate	1	3	3
E08	Senior Petty Officer	STS	Sonar Tech (Submarine)	1	0	0
E09	Master Chief Petty Officer	EM	Electricians Mate	1	0	0
E09	Master Chief Petty Officer	MM	Machinists Mate	1	0	0
Total				124	120	104

Appendix B: International Coordination of Arctic Research

A number of organizations have laid out research plans for the Arctic. The science conducted by a dedicated science submarine would augment the activities described by these plans. These research plans outline both important opportunities and challenges for such a submarine. They point to critical measurements unobtainable from current platforms which a submarine could provide. However, these plans often express the expectation that new technologies may be able to begin providing these measures at low cost sometime over the coming decade.

Internationally, the challenge of global climate change has fostered several international organizations to coordinate scientific efforts to understand and predict climate variations, and to provide guidance to policymakers. These in turn have spurred the development of international programs to coordinate global observations of physical, chemical, and biological variables of the ocean/atmosphere system. UNESCO, through UNEP, has taken a lead in many international efforts, coordinating programs through its Intergovernmental Oceanographic Commission (IOC) and Intergovernmental Panel on Climate Change (IPCC), as has other organizations such as the World Meteorological Organization (WMO), the Scientific Committee on Oceanographic Research (SCOR), and the related World Climate Research Program (WCRP). Many large-scale scientific studies have been implemented by these programs, such as the Tropical Ocean and Global Atmosphere Program (TOGA), the Global Investigation of Pollution in the Marine Environment (GIPME), the World Ocean Circulation Experiment (WOCE), the Global Energy and Water Cycle Experiment (GEWEX), the Joint Global Ocean Flux Experiment (JGOFS), and the International Geosphere/Biosphere Program (IGBP). A central aim of many of these programs has been to design and develop a continuous, synoptic, worldwide climate and weather monitoring system, and a high-level plan for such a system has been proposed called the Integrated Global Observing Strategy (IGOS), sponsored jointly by many of the world's space agencies. Three main operational elements of this system have been organized, called the Global Terrestrial Observing System (GTOS), the Global Climate Observing System (GCOS), and the Global Ocean Observing System (GOOS). A detailed plan for the design and implementation of GOOS was developed by the Ocean Observing System Development Panel (OOSDP) between 1990 and 1995, was summarized in its final report.[1] The OOSDP was replaced in 1996 by the Ocean Observations Panel for Climate, which has continued to refine those plans and begin implementation.

The OOSDP report articulates a well-defined operational plan for a global ocean observing system, from which one may draw insight as to how a DNSS could be utilized and add value. As envisioned, the GOOS system would measure a variety of important climate variables such as ocean temperature, salinity, currents, carbon, and sea ice, on spatial grid coverages that are worldwide and at considerably

[1]OOSDP final report (1995) by the Ocean Observing System Development Panel sponsored by the IOC and the Joint Scientific Committee of the International Council of Scientific Unions "Scientific Design for the Common Module of the Global Ocean Observing System and the Global Climate Observing System."

higher resolution than is currently available. The report also makes clear that it is vital to begin ongoing, synoptic, and routine monitoring of all variables in time, since unbroken time history is critical for predictive modeling and observation of climate changes. The OOSDP report describes a variety of existing and developing platforms and sensor technologies that should be utilized. For the ice-free oceans, a combination of satellites, surface research ships and ships-of-opportunity, moored surface and sub-surface buoys, drifting surface buoys, and autonomous floats are expected to provide most of the necessary coverage. In addition, the report claims that developing technologies which should be available within 10 years, such as relatively cheap and reliable autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs), rapid CDT profiling, ocean acoustic tomography, and new satellite-monitoring techniques, will soon begin to make more expensive methods such as surface ship sampling unnecessary. Ice-covered regions have somewhat more difficult operational restrictions but, because of their sensitivity to global climate change, are particularly important to monitor. In these regions it is important to measure sea ice coverage and thickness, as well as other ocean climatic variables, however historically surface ship operations have been very difficult. As such, the OOSDP report envisions that most likely within a decade, large numbers of cheap AUVs and passive acoustic methods can be used to reliably measure these climatic variables.

The OOSDP plan has two important implications for the proposal to convert a nuclear-powered submarine to an unclassified research vessel. First, worldwide coverage of climatic observations in the ice-free oceans may be achieved within a decade using a variety of cost effective platforms and technologies. Second, although synoptic observations of the ice-covered oceans are still problematic, the deployment of new technologies, such as large numbers of autonomous platforms and new acoustic and satellite techniques, may also provide relatively cost-effective coverage in these areas within a decade.

Similar efforts to coordinate the study of global climate change and devise an integrated ocean observing system have taken place in the United States as well. The establishment of the U.S. Global Change Research Program (USGCRP) has resulted in significant increases in funding for large-scale ocean science research, which has in turn resulted in formal interagency cooperative efforts, with the National Science Foundation (NSF) playing a key role.[2] Other agencies involved in USGCRP include NASA, the Office of Naval Research (ONR), the Department of Energy (DOE), and the Department of Commerce's National Oceanic and Atmospheric Administration (NOAA). These agency and interagency efforts have supported several large-scale scientific observational programs, some of which are U.S. components of the international programs, such as the Ocean Drilling Program (ODP), the Climate Variability and Predictability Program (CLIVAR), the Global Ocean Ecosystems Dynamics program (GLOBEC), the U.S. JGOFS component, and the Ridge Interdisciplinary Global Experiments (RIDGE). Additionally, in FY 1997, Public Law 104-201 established the National Oceanographic Partnership Program (NOPP) to strengthen and coordinate oceanographic research among academia, private industry, the U.S. Navy, and 12 federal agencies, with a governing body being established called the National Ocean Research Leadership Council (NORLC). In August 1998, Congress charged the NORLC to "propose a plan to achieve a truly integrated ocean observing system."

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[2]See for example *Global Ocean Science: Toward an Integrated Approach*, Ocean Studies Board, National Academy Press (1999).

A detailed summary of this proposed system is contained in a recent report by the NOPP[3], submitted to Congress in February 1999, which draws upon a broad-based consensus of federal and non-federal scientists, with input from the Steering Committee for the international GOOS program and advice from the U.S. GOOS Steering Committee, and approved by the NORLC.

The NOPP plan for the U.S. ocean observing system follows closely, and integrates with the international GOOS plan, but in addition takes advantage of the peculiar strengths of the U.S. oceanographic research community, such as the extensive monitoring capabilities of the U.S. Navy. The report states that such an integrated observing system "serves the broad public good," specifically with respect to seven major societal needs, of which global climate change and national security are conspicuous. To serve these needs, a variety of ocean climatic variables need to be monitored in both U.S. territorial waters and in various global regions. The variables include surface currents, winds, air-sea fluxes of heat and water, nutrients and biologic productivity, carbon inventories, sea surface salinity and temperature, subsurface salinity and temperature, bathymetry, ambient noise, and sea ice conditions. Many of these variables cannot now be measured to sufficient accuracy or coverage to provide useful global climatic information. In particular, the report states that sea ice extent and concentration is intimately related to global fluxes of heat and freshwater, and that there is a "need to estimate ice thickness, and thus volume, on a continuing basis, but a methodology for routine measurement at reasonable cost does not now exist." These measurements are not only important for climate change, but routine monitoring of ocean states will become increasingly important for U.S. Naval operations and national security in general.

The NOPP implementation plan for the ocean observing system recommends a mix of technologies and platforms, both to complement the strengths and weaknesses of each, and also to provide cross-validation and calibration of individual methods. Additionally, the report stresses that because of the large coverage and continuity of the observational systems that is required, cost effectiveness and efficiency is a high priority. Technologies and platforms specifically outlined in the report include satellites, surface research and survey vessels, vessels-of-opportunity, moored surface and sub-surface buoys, drifting surface buoys and floats, expendable salinity-temperature-bathymetry probes, and large arrays of acoustic sensors. In addition, the report claims that new technologies that will be available within 10 years include cheap AUVs and profiling floats, acoustic ocean thermometry, and the capability of satellites to reliably measure additional climatic variables.

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[3] *Toward a US Plan for an Integrated, Sustained Ocean Observing System,* http://core.cast.msstate.edu/NOPPobsplan.html.

Appendix C: Background Information on Priority Research Areas

Climate Change in the Arctic

In recent years, there has been growing evidence of climate change in the Arctic, much of it suggesting an overall warming in the region. The most compelling observations include historical satellite images that document a decrease in the extent of sea ice and submarine measurements that have recorded a large decrease in ice thickness over the past 30 years. A key challenge is to understand the origin of these changes and to identify the links to global climate change processes. These efforts are motivated from several perspectives. First, a broad range of global climate models suggests that global climate change effects will be amplified in the Arctic. Thus, the region may provide "indicators" of global climate change processes that are more difficult to interpret in the temperate regions. Second, there is a significant potential for coupling between the Arctic Ocean and the downwelling arm of the global thermohaline circulation that originates in the North Atlantic. That is, perturbations in the Arctic climate have the potential to propagate into much larger effects in the temperate regions. Third, the Arctic climate system is characterized by a complex interrelationships and feedback mechanisms that have the potential to generate "run away" phenomena in response to small perturbations. Thus, there is a need to understand if the observed changes will grow into much larger effects. Finally, the Arctic climate system varies on time scales ranging from the inter-seasonal to decadal and millennial intervals. Finally, all climate systems, including the Arctic vary on time scales ranging from the inter-seasonal to decadal and millennial intervals. Thus, there is a fundamental ambiguity regarding the interpretation of climate variability.

Research on these questions involves a coordinated campaign of modeling and field studies. Within the United States, many of these efforts are supported by a large program within the Office of Polar Programs at the National Science Foundation (Arctic System Science) with the following goals:

- to understand the physical, geological, chemical, biological, and social processes of the Arctic system that interact with the total Earth system and thus contribute to or are influenced by global change, in order
- to advance the scientific basis for predicting environmental change on a seasonal-to-centuries time scale, and for formulating policy options in response to the anticipated impacts of global changes on human beings and societal support systems.

Within the NSF program, there has been a large effort to develop a comprehensive framework to organize the top-level research questions for Arctic climate change (see Appendix B for a full discussion of these). The three principal questions are:

- What is the role of the Arctic in the global system (past, present, and future)?

- What are the types and sources of global change in the Arctic?
- What are the effects of changes on climate, chemistry, ecosystems, and humans?

These efforts are complemented by a wide range of international programs, emphasizing cooperative international research in the Arctic (see Appendix B for a detailed discussion of international programs). For example, the Arctic Climate System Study carried out as part of the World Climate Research Program is focused on the following objectives, which are related to the NSF goals:

- understanding the interactions between the Arctic Ocean circulation, ice cover, and the hydrological cycle;
- initiating long-term climate research and monitoring programmes for the Arctic; and
- providing a scientific basis for an accurate representation of Arctic processes in global climate models.

Formally, all international research in the Arctic is coordinated through the non-governmental International Arctic Science Committee, though this involves a much broader research agenda that extends beyond climate change to questions of sustainable development, pollution, and the health of indigenous populations. To support these, and other objectives, critical data sets are collected from the atmosphere, Arctic Ocean, sea ice, terrestrial environments, and the sea floor using a wide range of research platforms. As emphasized by the recent report *Logistics Recommendations for an Improved U.S. Arctic Research Capability*[1], these efforts are challenged by the harsh working conditions and perennial ice cover over much of the Arctic. In this environment, SSN 686 would have a unique capability to maneuver freely throughout the Arctic Basin, under the ice. However, it would operate in an environment where a large number of facilities have been deployed to meet current research needs. For example:

Surface Heat Budget of the Arctic Ocean (SHEBA): SHEBA is a comprehensive field and modeling experiment designed to improve predictions of the Arctic climate by investigating the physical processes that determine the surface energy budget, sea ice mass balance, and surface radiative properties of the Arctic Ocean. The project involves three phases over eight years. Phase 1 (1995–1997) involved modeling and analysis of existing data sets. Phase 2 (1997–1999) was a multiseason field experiment on the drifting ice in the Arctic, involving an icebreaker and extensive instrumentation (see Figure C.1). Phase 3 (2000–2003) will analyze the field data and update predictive climate models for the Arctic. NSF, together with a broad range of U.S. agencies, has provided the principal support for SHEBA. Additional support has been provided by the governments of Japan and Canada.

The picture in Figure C.2 shows the full range of measurement facilities for the SHEBA research camp on the pack ice (1) Satellite remote sensors monitor the atmosphere and the surface: NOAA AVHRR, and TOVS, RADARSAT ScanSAR, DMSP SSM/I. (2) Research aircraft to measure cloud properties, atmospheric structure and surface parameters. (3) Weather balloon (RAWINSONDE) flights twice per day measure vertical profiles of temperature, humidity, and wind. (4) Tethered balloon system to

[1] *Logistics Recommendations for an Improved U.S. Arctic Research Capability*, U.S. Arctic Research Commission, 1997, 99 pages.

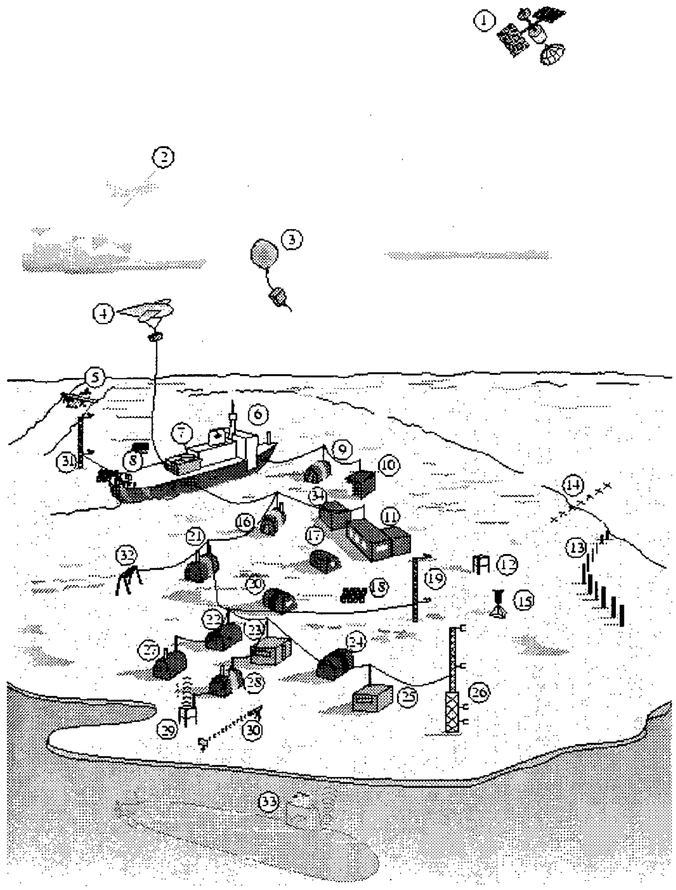

Figure C.2 SHEBA Research Camp

measure thermodynamic structure, cloud properties, and radiation in the atmospheric boundary layer (ABL). (5) Ice runway and STOL aircraft to transport people, equipment, and supplies between the station and Alaska. (6) Heavy icebreaker CGS *Des Groseilliers* serves as the hotel, power station, engineering center, and communications base for the ice station. (7) Orange transportainer (the "pumpkin") on the aft flight deck houses power and data acquisition equipment for the D.O.E. Atmospheric Radiation Measurement (ARM) SHEBA instrumentation. SHEBA's millimeter cloud radar is mounted on the roof of the ARM pumpkin. (8) ARM instruments, including: laser ceilometer (ceiling height), microwave radiometer (water vapor and liquid water content), microwave temperature profiler, whole-sky imager, and SKYRAD radiometer suite (incident spectral irradiance, including direct and diffuse shortwave irradiance); and SHEBA's DABUL LIDAR for measuring properties of atmospheric ice and aerosol. (9) Weatherport shelter housing Acoustic Doppler Current Profiler (ADCP) for measuring ocean currents and turbulence (deep unit). This shelter is also used as a staging area for the RAWINSONDE launches, and for data acquisition with the Fourier Transfer Infrared Radiometer (FTIR). (10) ARM Atmospheric Emitted Radiometer Interferometer (AERI). The

FTIR and the ARM AERI measure the spectrum of incident longwave radiation. (11) Marine Biology Laboratory "Blue Bayou" for water sampling, ice sampling, and diving. (12) Ventilated shelter for maximum and minimum thermometers. (13) Snow and ice mass balance station, represented by ablation stakes. (14) Snow and ice heat and mass balance instruments in a transect across a pressure ridge. (15) Nipher snow gauge for measuring precipitation amount. (16) Ice station logistics shelter—tools and hardware. (17) Cold storage ParkAll for the Marine Biology program. (18) Fuel drums. (19) 10 m tower for standard surface meteorological time series measurements. (21) Storage shelter for snow and ice physics program. (22) Shelter for emergency generator and power distribution. (23) Ocean city hut housing Yoyo CTD winch for time series profiles of temperature and salinity. (24) Cold storage for the atmospheric flux program. (25) Metropolis hut housing computers and equipment for the atmospheric flux program. (26) 20 m tower and scaffold with sonic anemometers for measuring turbulent fluxes. (27) Weatherport shelter housing ADCP (shallow unit). (28) Weatherport shelter housing upper ocean turbulence mast. (29) SODAR for measuring temperature profiles and inversion height in the ABL. (30) Scintillometer for measuring spatially averaged surface turbulent heat flux. (31) 10 m tower for standard surface meteorological time series measurements. (32) ARM program GRNDRAD stand for measuring the surface upward spectral irradiances. (33) U.S. SSN submarine, measuring sea ice draft distribution spatial statistics under the SCICEX program (Hawkbill and Archerfish).

Figure C.1 Image of the SHEBA ice camp, showing the Canadian icebreaker *Des Groseilliers*, frozen into the ice with surrounding measurement facilities

Paleoclimates of Arctic Lakes and Estuaries: This project involves a range of investigations that seek to describe the range of spatial and temporal variations in the Arctic climate on interannual-to-millenial time scales as indicated by proxies preserved in lacustrine and estuarine sediments. The project has supported field research in Alaska, Iceland, Canada, and Russia. It also supports and extensive analysis and modeling effort to interpret the data. It is supported by NSF.

Land Ice Interactions: The goal for this NSF-supported project is to enhance the understanding of land-ice interactions in the Arctic and their influence on climate. Many of the individual research projects have focused on the flux of trace gasses in northern Alaska to quantify the role of the tundra as a source or sink for CO_2. Another important component has involved participation in the International Tundra Experiment which uses greenhouses to passively warm the tundra at 26 circumpolar sites in 11 countries. The purpose of the experiment is monitor the capacity of tundra plant communities to respond to environmental change.

USCGC Healy *Acquisition*: On November 15, 1997, the U.S. Coast Guard launched the USCGC *Healy* to serve the primary mission as a world-class, high-latitude research platform. Built at an approximate cost of $186 million, it will be deployed in icebreaking operations during all seasons in the Arctic and Antarctic. The *Healy* is designed to conduct a wide range of research activities, providing more than 4,200 square feet of lab space, numerous electronic sensor systems, oceanographic winches, and accommodations for up to 50 scientists. The *Healy* is designed to break 1.37 m of ice continuously at three knots and can operate in temperatures as low as –38° C. The Healy is the third U.S. icebreaker operated by the Coast Guard. Support for scientific cruises will be provided by NSF. The scientific community has begun a planning process to identify high-priority measurements for the first cruises.

SCICEX: Originating with a memorandum of agreement between the Navy and the civilian science agencies, the SCICEX program provided the first opportunity to carry out unclassified scientific measurements from SSN 637-class submarines operating in the Arctic Ocean. Six cruises from 1993–1999 collected a broad range of data on the bathymetry, hydrography, ocean chemistry, ice thickness, and pollution throughout the Arctic Basin. Support for the civilian research activities was provided by NSF and the Office of Naval Research. A portion of the support included development, installation, and operation of a specialized submarine sonar-mapping unit for high-resolution surveys of ocean bathymetry.

Arctic Climate System Study (ACSYS): Noted above, this international project coordinates a wide range of nationally funded efforts from different countries into a broad research agenda. The work encompasses six focus areas, each with a detailed research plan. The titles for these efforts are the Arctic Ocean Circulation Program, Arctic Sea Ice Program, Arctic Atmosphere Program, Hydrological Cycle in the Arctic Region, ACSYS Modeling Program, and the Data Management and Information Panel, indicating a comprehensive data-gathering and analysis efforts.

Geologic and Geophysical Exploration in the Arctic Basin

For the past 40 years, there has been a broad effort to study the geology and geophysics of the ocean basins throughout the world. These data have contributed to fundamental discoveries and understanding regarding plate tectonics, mineral and fossil fuel deposits, geologic history, and even the origin of life on Earth. With this background, there has been a natural interest in extending this research into the Arctic Basin. However, these efforts have been limited by the ice conditions that preclude all but specialized oceanographic expeditions. If it were possible to carry out systematic surveys under the Arctic ice, the data would contribute to two important research goals: elucidation of the slowest spreading ridge in the global plate tectonic system (the Gakkel Ridge) and constraints on the geologic history of the Amerasian Basin. Studies on the first issue have implications far beyond the Arctic because the results would contribute to the fundamental understanding of plate tectonics. Studies on the second would contribute to a range of geologic and climate change research in the region. Preliminary results from limited surveys indicate that the geology of this basin is extremely complex, involving a number of submerged continental fragments. There may also be vast deposits of methane hydrates in this region, with important implications for global climate. Much of this research requires surveys over broad regions, suggesting that a submarine could make a strong contribution because of its capability to navigate under the ice. Examples of current Arctic research on geology and geophysics include the following:

InterRidge Project to Map and Sample the Arctic Ridges: This is an international offshoot of a U.S. Project (RIDGE) to carry out comprehensive studies of spreading ridges throughout the world's oceans. For the Gakkel Ridge, the scientific questions are related to mantle processes, melt production, and transport at extremely slow spreading rates. This work will require systematic surveys (bathymetry, seismic, and gravity) and sampling along the ridge. Additional biogeochemical research would involve direct monitoring of ridge environment on the Gakkel and Knipovich ridges. There is also great interest in mapping the structures associated with the termination the Gakkel Ridge against the Laptev Shelf in the Russian exclusive economic zone. The past SCICEX cruises have made an important contribution to this effort by collecting detailed bathymetric, sub-bottom profiles, and gravity data over a large portion of the Gakkel Ridge. Future research efforts for this project are focused on icebreaker cruises to carry out sampling and seismic surveys along the ridge.

Nansen Arctic Drilling Program: This is an international group of scientists and institutions, working together to develop a coordinated research initiative for drilling in the Arctic Ocean Basin. This effort serves two scientific goals: (1) to recover geologic samples to provide a continuous record of the Arctic climate extending back to the Cretaceous Period and (2) to recover samples and document structures that constrain the geologic evolution of the Arctic Basin. While ocean drilling is part of a large international effort in the ice-free oceans, collecting data and samples from over a large number of sites, there has been no drilling in the Arctic Ocean because of the logistical challenges. Thus, an important prerequisite for this effort is to collect detailed survey information (bathymetric and seismic refraction) to identify accessible sites that could also provide valuable data. SCICEX and past icebreaker cruises have collected data along the Lomonosov Ridge that is suitable for this purpose.

Arctic Gravity Project: This is an international effort to compile a public-domain gravity grid of the Arctic gravity field north of 64° N. The participating countries for this effort are the United States, Canada, Russia, Norway, France, Sweden, Finland, Germany, Great Britain, and Iceland. The focus of the gravity grid will be the Arctic Ocean, Greenland, and the continental areas of North America and Russia north of 64° N. The project has been stimulated by recent advances in data collection technology, notably the advent of airborne gravimetry, the development of satellite altimetry over ice-covered regions, and the availability of gravity data from SCICEX cruises. The initial part of the project has focused on the collection of these databases, either from existing sensors or archival sources. After the data are compiled, there will be a large analytical effort to combine the data into a single geoid model for the region. This will be the first accurate geoid model for the entire Arctic region and will provide fundamental constraints for a range of geologic and geophysical studies.

International Bathymetric Chart of the Arctic Ocean: The goal of this initiative is to develop a digital database containing all available bathymetric data north of 64° N, for use by mapmakers, researchers, and others whose work requires a detailed and accurate knowledge of the depth and the shape of the Arctic seabed. Initiated in 1997, this undertaking has so far engaged the volunteer efforts of investigators who are affiliated with eleven institutions in eight countries: Canada, Denmark, Germany, Iceland, Norway, Russia, Sweden, and the United States. The activity has also been endorsed and/or supported financially by the Intergovernmental Oceanographic Commission, the International Arctic Science Committee, the International Hydrographic Organization, the U.S. Office of Naval Research, and the U.S. National Geophysical Data Center. SCICEX data, together with declassified soundings from past U.S. and British Navy cruises, have made an important contributions to this effort.

SCICEX: As noted above, the SCICEX cruises have made important contributions to a number of geologic and geophysical projects in the Arctic. For these efforts, the most important data have been obtained from a specialized hull-mounted, side-scan sonar system: the Submarine Characterization and Mapping Pod (SCAMP), together with a sub-bottom profiler (see Box 3). Gravity surveys from an onboard gravimeter have also been valuable because the resolution is enhanced compared to aerial measurements collected by airplanes or satellites

Understanding the Dynamics of the Bering Sea Ecosystem

The Bering Sea ecosystem supports a vast range of fish, birds, and mammals that play a vital role in the larger Arctic ecosystem and the livelihoods of the local population. Measured in dollar terms, its fisheries are also an important contributor to overall economy of the western United States. However, biological studies indicate that the overall ecosystem is under stress, as reflected the reduced diversity of fish species and the reduced fish populations. There are a range of proposals to explain these observations, including climate change, pollution, complex interactions between species mediated through the food chain and climate, and impacts from commercial fishing. Testing these hypotheses will require comprehensive monitoring of the ecosystem, including under-ice measurements where a submarine could be valuable.

In the past few years, at least 10 separate agencies and institutions have expressed concerns about the environmental changes in the Bering Sea and have developed science plans addressing different parts of the problem. The U.S. Arctic Research Commission has also identified "Studies of the Bering Sea Region" as one of its four priorities for basic research in the Arctic. In this setting, scientists from the National Oceanic and Atmospheric Administration, the Department of Interior, and the Alaska Department of Fish and Game have organized an integrated research plan to coordinate the full range of these efforts. The current effort is organized around two end-member hypotheses that span the current management and science issues in the Bering Sea:

- Natural variability in the physical environment causes shifts in trophic structure and changes in the overall productivity of the Bering Sea.
- Human impact leads to environmental degradation, including increased levels of contaminants, loss of habitats, and increased mortality on certain species in the ecosystem that may trigger changes in species composition and abundance.

To test hypotheses, a structured research plan, involving monitoring modeling, process studies, and retrospective analysis, has been developed for five theme areas. These are variability and mechanisms in the physical environment, individual species responses, food web dynamics, contaminants and other introductions, and the habitat.

Oceanographic Studies in the Ice-Free Oceans

Research in the ice-free oceans addresses a range of scientific questions and objectives. From the perspective of basic research, this effort is focused in three general areas: elucidating the connection between ocean processes and global climate, understanding the health and sustainability of critical ocean ecosystems, and characterizing the geology and geophysics of the marine basins. The motivation for this work can be expressed in societal and intellectual frameworks. For example the recent report, *Opportunities in the Ocean Sciences: Challenges on the Horizon,*[2] from the Ocean Studies Board of the National Research Council states:

> On the occasion of the International Year of the Ocean, the Ocean Studies Board has identified three broad research areas that present great opportunities for advances in the ocean sciences and will lead to concrete improvements for human life on this planet.
>
> - *Improving the health and productivity of coastal oceans*—A large fraction of the U.S. population lives, works, or plays within 50 miles of the coast. Marine fisheries, shipping, and recreation are major industries. A more comprehensive, basic understanding of the coastal oceans and their interaction with the land is needed that will be applicable to all coastal areas and so provide cost-effective, accurate management advice.
> - *Sustaining ocean ecosystems for future generations*—The ocean, from the coast out to the deepest abyss, sustains a vast, interconnected web of animal and plant life. This living system provides food and medicines, filters and transforms many human-generated substances, and affects the climate in complex ways. The effects of natural and anthropogenic change on marine ecosystems need to be evaluated and quantified to sustain, for generations, the biodiversity and productivity we increasingly depend on in the oceans.
> - *Predicting climate variations over a human lifetime*—Any significant change in the earth's climate has profound impacts on agriculture, water availability, plant and animal life, and patterns of human settlement and migration. The ocean plays a central role in controlling climate through heat storage and transport and gas exchange with the atmosphere. Changes in marine life and storage of materials in sediments indirectly affect these processes. The complex interplay between climate, ocean circulation, and ocean biogeochemistry needs to be understood in the context of evidence from the past in order to predict climate fluctuations and understand their impacts.

[2] *Opportunities in the Ocean Sciences: Challenges on the Horizon*, National Research Council, National Academy Press, Washington, D.C., 1998.

Similarly, a research agenda for marine geology and geophysics was recently articulated in an NSF workshop report. The following passage illustrates the interconnection between societal concerns and fundamental research challenges:

> Many of the research topics central to marine geology and geophysics address issues of societal concern, such as changing climate, coastal pollution and erosion, and earthquake hazards. In some cases, there has been pressure to implement solutions to these problems without a complete understanding of these complicated systems. Even worse, some of these systems are now demonstrated to be highly non-linear, such that input at one frequency can produce a response at very different frequencies.[3]

To carry out this research, U.S. national and international programs support a vast range of data collection facilities that include large fleets of oceanographic research ships and platforms, satellites for remote sensing, drifting buoys for autonomous data collection, submersibles and remotely operated vehicles for research and sampling at great depths, AUVs, ocean drill rigs, ocean bottom seismometers, and hydro-acoustic monitoring facilities. Detailed planning and operations for these facilities are executed by a large number of non-government organizations, agencies, and international experiments, which operate in a remarkably coordinated fashion given the diversity of the overall effort (see Appendix B). Almost all research facilities play a "dual use" role, supporting different research efforts carried out by different disciplines (e.g., marine geophysics and biogeochemistry). In addition to basic research, facilities are also used to collect important data for operational missions carried out by the U.S. Navy and commercial maritime activities. Within the United States, these efforts involve support from NSF, National Oceanographic and Atmospheric Administration, NASA, the Environmental Protection Agency, the Department of Defense, Department of Energy, the U.S. Coast Guard, and the U.S. Geological Survey.

With such a diverse constituency for ocean research, there has been a great effort to identify the next generation of data-gathering facilities and platforms. As detailed in the recent report, *An Integrated Ocean Observation Plan,* signed by 1,832 members of the ocean sciences community, there is a need for a coordinated data gathering and archiving strategy to facilitate the widest possible dissemination and impact of ocean data (see Figure 3).[4] The report highlights the need for networks of autonomous sensors collecting data from a wide range of ocean environments (e.g., coastal regions, interior oceans regions, upper oceans, surface fields, and fluxes). The overall goal is to address one of the primary research applications for a submarine in the open oceans, as identified by the scientific community. Specifically, the autonomous sensors would be used continuous monitoring of the upper water column (1,000 m) in remote regions and rough seas.

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[3] *The Future of Marine Geology and Geophysics,* Report of a Workshop, Ashland Hills, Oregon, December 5–7, 1996, 70 pages; p. 4.
[4] *Toward a U.S. Plan for an Integrated, Sustained Ocean Observing System,* http://core.cast.msstate.edu/NOPPobsplan.html.

Appendix D: Developments in AUV/ROV Technology

Currently available autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) have important capabilities but can only operate in the vicinity of a host platform such as a surface ship, submarine, or ice camp. Thus, as discussed in Chapters 2 and 3, currently available AUV and ROV technology is an important complement to a dedicated science submarine and such vehicles do not compete with any of the submarine's unique capabilities. However, AUV technology is an area of rapid development and the capabilities of these vehicles may increase significantly within a time horizon relevant to decisionmakers involved with a dedicated science submarine. The decision problem posed by these potentially rapid AUV developments and a scenario-based structure for assessing them is sketched briefly at the end of Chapter 3. Here we provide a brief review of these ongoing technological activities.

The number of researchers, institutes, and private companies developing AUVs and ROVs has grown quickly this decade, and they have begun to establish organizations to coordinate activities.[1] For example, the Association for Unmanned Vehicle Systems International (AUVSI), the U.S. Navy, the IEEE Ocean Engineering Society, and the Marine Technology Society coordinate many efforts and are extensive sources of information and contacts; and an Autonomous Undersea Systems Consortium is in development. In addition, many western European countries, particularly the UK and France, as well as a number of other countries worldwide, have ongoing AUV and ROV research programs. Many university, governmental, and private research institutes exist in the United States, and many have developed prototypes of vehicles or related systems.

The development of technical systems pertaining to AUVs can be divided into three broad categories: platforms, communications, and sensors.[2] Current platforms are already relatively robust, with a developed engineering background. Typical lengths of various AUVs are on the order of one to two meters, with bulk weights in the range of a few hundred pounds. Operational ranges are at least 1,000 km, and this is improving rapidly, and cruising speeds are on the order of a few knots. Depth ranges extend to 6,000 m, making most of the ocean depths accessible worldwide. Currently, the two principal technical challenges are power supply and navigation. The majority of existing platforms utilize various battery technologies, such as high-efficiency lithium sources, although fuel cells and even solar power sources[3] are in development. Autonomous navigation capabilities appear to be more problematic, since conventional methods such as dead reckoning, inertial guidance, and acoustic triangulation all have accuracy or miniaturization constraints. Terrain-based navigation has potential and is being explored, although this may be hindered by the lack of accurate topographic maps for most

[1]For a list of such institutions see http://www.cacs.louisiana.edu/~kimon/AUV.

[2]J.R. Fricke, "Down to the Sea in Robots," *Technology Review*, Massachusetts Institute of Technology (October 1994).

[3]For example, see D. B. Blidberg, "Solar Powered Autonomous Undersea Vehicles," Autonomous Undersea Systems Institute, Lee, N. H. (1996).

of the Earth's seafloor. However, even modest improvements in autonomous navigation capabilities could yield significant improvements in AUV capabilities.

Perhaps the greatest increase in the capabilities of AUVs could come from developments in communications and networking. Since electromagnetic signals propagate poorly in the ocean, subsurface communications have conventionally relied on acoustics. Recent research has produced digital acoustic transmission systems, capable of compensating for the changing characteristics of the propagation channel, which can transmit at greater than 1,200 baud, and much higher rates are possible in the near future. Further performance increases may be obtainable by integrating many AUVs into acoustic local area networks (ALANs), much like cellular phone systems, and providing either floating or shore-based electromagnetic links to radio or satellite systems. Such system architecture can provide rapid, worldwide communications and the potential capability to control the operations of large numbers of AUVs remotely through the Internet from a researcher's desktop. Small prototype ALAN systems have already been tested in open-ocean research. ALANs can also provide the potential to perform synoptic ocean measurements over large areas, and for automated platform control of multiple AUVs via distributed artificial intelligence methods.

The third area of AUV technology required for their role in oceanographic operations is onboard sensors. Size, weight, and power constraints of the sensors are the significant engineering concerns, as are the typical temperatures and pressures which submersibles can be subjected to in the ocean. However this technology is developing dramatically. Chemical sensors based on tiny fiber optic probes, and silicon-chip based detectors for amino acids, are already being tested, and can detect the presence of a large variety of chemical and biological compounds. In general, sonar technology is already well developed for various platform types including AUVs, however simulating large synthetic acoustic arrays using fleets of highly mobile AUVs could provide rapid, high-resolution acoustic mapping and survey of large areas of the ocean. A variety of small, autonomous, low-power physical oceanographic instruments now exist which can be carried by AUVs, and are capable of measuring temperature, salinity (via conductivity), depth, currents, and small-scale turbulence. Again, data sharing and networking of many AUVs distributed over large physical areas could provide the capability to make in situ, synoptic measurements of ocean variables with a speed and resolution beyond any current capabilities.

An interesting example of AUV technology for Arctic applications is being developed by a group led by James Bellingham at the Monterey Bay Aquarium Research Institute. This group has designed a state-of-the-art AUV-sensing platform for use in the Arctic, specifically to measure hydrography and track the warm Atlantic water intrusion into the Arctic Basin (the ALTEX experiment). This platform has a modular design with an articulated tail section, is only about 0.5 m in diameter, and is powered by an aluminum/peroxide fuel cell. Operational characteristics include a range of up to 1,400 km, a cruising speed of up to three knots, and a depth rating of 4,500 m, and it will be capable of fully autonomous operations for up to two weeks. The most novel characteristic of this design is its communications system, facilitated by 14 expendable telemetry buoys. After acquiring hydrographic data, the AUV downloads the data to a buoy, which is released and ascends to the ice interface, melts through the ice using an exothermic chemical, obtains a GPS position fix, then transmits all data to the Argos satellite.

In this way, the AUV is capable of making full water column hydrographic assessments and transmitting them on a daily basis, for up to two weeks.

All of the mechanical components of ALTEX AUV have been successively tested. In spring 2000, the fuel cell was successfully run for 170 hours. There was a separate successful test of the systems for melting through ice to allow satellite communications. There will be continued testing of the fuel cell through next spring, 2001, with the goal of operating for 340 hours. The full unit will be tested, along with the navigation systems, in the Arctic in 2001, deployed from the icebreaker *Healey*, on one of its first research cruises. In the past 2–3 years, the first scientific papers were published using AUV data. A recent report from the National Research Council made broad recommendations promoting AUV development for oceanographic research. There are seven commercial companies selling off-the-shelf AUV systems for a wide range of applications. There appears to be much interest among the scientific community in the capability of AUV developments to address important research problems.

Given the above technical and operational capabilities that could be available within a few years, a large number of practical applications for AUVs have already been proposed. These include: in prospecting, facility construction, and equipment inspections for the underwater petroleum production industry; monitoring, tagging, and even acoustic herding of fish stocks; and detection of toxic algal blooms in the shellfish industry; monitoring and mapping pollutant distributions, such as oil spills, sewage, and radioactive waste; routine, high-resolution, and large-scale weather monitoring using meteorological packages to assess the ocean/atmosphere interface; routine monitoring and assessment of deep ocean variables for global climate change; routine generation and updating of bathymetric charts and current maps; and any hazardous subsurface duty, such as salvage or emergency recovery.

A important potential advantage that AUVs have in all of these applications is cost, with the cheapest vehicles currently costing tens of thousands of dollars. Mass production of these units in the future could lower even these costs significantly.

AUV technology has many applications in the warm, ice-free oceanic regions, and could replace many costly conventional oceanographic platforms. However, they may be particularly valuable in the ice-covered ocean areas, where operation of existing platforms other than a dedicated science submarine is difficult or even impossible. At present, scientific and programmatic collaborations are being considered between NASA, NOAA, the U.S. Coast Guard, and the NSF's Polar Research Programs to share deep space unmanned probe technologies and deep ocean technologies, and to integrate these into existing oceanographic support infrastructures. Potential plans include regional deployment of large numbers of ROVs and AUVs from icebreakers and by airdrop; small unmanned docking stations to provide onsite power regeneration and satellite communication links; equipping of autonomous platforms with a variety of recently developed miniaturized and low-power sensors for physical, chemical, and biological measurements; advanced, integrated acoustic and electromagnetic communications networks to provide remote control and large-scale areal sensing; and seamless computer/human network interfaces whereby human operators at very remote locations can control platform operations in near–real time.

The full development of the above technologies may make possible the cost-effective study and monitoring of a large number of important physical and biochemical processes in both Arctic and Antarctic regions.[4] For example, monitoring of temperature, salinity and currents on fine physical (sub-meter) and temporal scales; the study of hydrothermal vent systems; surveying of methane hydrate deposits; surveys of under-ice biological processes and productivity; studies of benthic processes; monitoring particulate fluxes (especially carbon) and fluxes of various gases—particularly carbon dioxide; bathymetric surveys; characterizing ocean acoustic properties; measurement of glacial retreat in shallow water regions; and perhaps most importantly large-scale surveys of ice volume and studies of ice dynamics, which may have critical importance to the Earth's climate. Many of the technologies required to perform these various tasks exist now, and many may be well developed within a decade. One of the main uncertainties governing the rate of AUV development is the level of funding for such efforts which will be made available by the government.

[4] "Science at the Extremes," report of the Arctic and Antarctic Undersea Workshop, April 15–17, 1998, sponsored by NOAA, NASA, and USCG.

Appendix E: Oceanographic Databases

Many of the principal U.S. and international database depositories for worldwide ocean observations are listed below, as are a few technical reports with descriptions of international depositories and data management systems.[1] Most of the Web sites listed have electronic user interfaces which allow data searches, downloads, access to technical information, and cross-links to other relevant sites. A description of the observation regions, platforms, and accuracy over which these data sets were generated is far beyond the scope of this report; however, a brief look through these sources offers a reasonably comprehensive grasp of the current state of the available observational knowledge about the world's oceans. Some principal information resources include:

International Oceanographic Data & Information Exchange (IODE) of UNESCO, see http://ioc.unesco.org/iode/index.htm

GCOS-13 (WMO/TD-No. 677), GCOS Data and Information Management Plan, Version 1.0, April 1995, see http://193.135.216.2/web/gcos/pub/dim_v1_1.html

The Joint Data and Information Management Plan of GOOS, GTOS, and GCOS, described in GOOS Publication No. 42, The GOOS 1998, IOC, Paris, 168 pp.

The STORET system of EPA, see http://www.epa.gov/owow/STORET

The EOS Data and Information System (EOSDIS) project of NASA, see http://spsosun.gsfc.nasa.gov/NewEOSDIS_Over.html

The National Oceanographic Data Center of NOAA/NESDIS, see http://www.nodc.noaa.gov

The Master Environmental Library of the Department of Defense, see http://www-mel.nrlmry.navy.mil

The Naval Oceanographic Office suite of ocean data and products, see http://128.160.23.51/noframe/select.products.htm

The data system for the Tropical Atmosphere Ocean (TAO) array, see http://www.pmel.noaa.gov/toga-tao/review98/data.html

Lists of oceanographic data servers at http://gcmd.gsfc.nasa.gov/pointers/ocean.html

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[1]From the report, "Toward a US Plan for an Integrated, Sustained Ocean Observing System," Appendix 3, NOPP, April 26, 1999, available at: http://core.cast.msstate.edu/NOPPobsplan.html.

The Distributed Oceanographic Data System (DODS) from the University of Rhode Island and the Massachusetts Institute of Technology, see http://rs.gso.uri.edu/DODS/home/home.html

The World Ocean Circulation Experiment (WOCE) of the NSF has a data information unit, see http://www.cms.udel.edu/woce

Metadata requirements of the Federal Geographic Data Committee, see http://www.fgdc.gov/metadata/metadata.html

Oceanographic Databases of the Arctic

Prior to the SCICEX cruises, the primary data collections efforts in the Arctic Ocean came from U.S. Navy nuclear submarines, and large Soviet activities that included ice camps and icebreakers. These data sets are not comprehensive, being both spatially and temporally sparse, and in addition most of them have been classified.

With the advent of the international efforts to study global climate variability, this picture is changing rapidly as well. Currently, a concerted effort is under way within the United States and internationally to focus Arctic research efforts and develop more comprehensive observing systems, as well as to centralize large preexisting databases from previous observations.

By far the largest single contribution of preexisting data came from the declassification of U.S. and former Soviet military oceanographic surveys. With the establishment of the Environmental Task Force in 1992 by the Director of Central Intelligence, at the behest of then-Senator Al Gore, various efforts were made to assess the possibility of declassifying large amounts of U.S. Navy oceanographic data assets. This resulted in the establishment of the MEDEA Special Task Force to examine the holdings of the Navy Meteorology and Oceanography Command; a 1995 report by that group gives a thorough overview of types of data then available.[2] The MEDEA report was instrumental in spurring the declassification and eventual release of a significant amount of Navy oceanographic data. An even more substantial effort to assemble Arctic hydrographic data has been spurred by the U.S.-Russian Joint Commission on Economic and Technological Cooperation (the Gore-Chernomyrdin Commission). The Environmental Working Group (EWG) established by this Commission has facilitated the collection and distribution of large amounts of formerly classified environmental data from U.S. and Russian national security assets. Recently, the EWG Subgroup on Arctic Climatology has developed an electronic atlas of in situ Arctic Ocean data over a 40-year period, assembled from U.S., Russian, and Canadian data assets. This data is currently distributed openly via CD from the National Snow and Ice Data Center of NOAA.

Another large source of in situ Arctic Ocean data has come from the six SCICEX cruises during the period of 1993–1999. These data were intended as a public scientific resource, and a variety of measurements were made of such variables as temperature, salinity, bathymetry, nutrients, and sea ice. A description of these data and many of the derived scientific studies is available in the report of the SCICEX 2000

[2] "Scientific Utility of Naval Environmental Data," MEDEA report, June 1995, available at: http://128.160.23.54/products/PUBS/medea/navy_etf.html.

Workshop.[3] In addition, a significant amount of acoustic data on sea ice distributions from historical U.S. Navy nuclear submarine surveys has been declassified and released, and much more will be processed and released in the future.[4]

Although the Arctic is by far the least observed ocean, a variety of other data sets are available from many sources, consisting of a spectrum of platforms, sensor technologies, and physical variables. For example, NASA holds large databases of satellite data about the Arctic, and its developing Earth Observing System program will collect and integrate such data on a much larger scale. To summarize all of these data sets in Arctic we have cross-referenced the type of platform used for past observations (e.g. surface ship) versus the relevant physical observable measured (e.g. temperature) (see Table 8). Entries in the matrix are numbers that reference a short description of the particular database and contact information given at the end of this section. With regards to these entries, it should be noted that most of the large database sites now have cross-referenced links, and often contain the same data as other sources, hence we have typically tried to list only one major source for a given data type. Also, we have tended to list those data sites that are comprehensive, in order to give as compact a listing as possible. This table is not meant to be entirely inclusive of all available data, which is far beyond the scope of this report, rather it is meant to give a short overview of the available coverage of the Arctic region.

In addition to the table entries, many other sites exist which contain comprehensive information about the Arctic, such as reports, bibliographies, metadata, and/or Web links to data depositories, research institutes, and program offices. A few of the major ones are listed below:

(1) The International Arctic Environment Data Directory
http://www.grida.no/add

(2) The Arctic Climate System Study (ACSYS) of the WCRP
http://www.npolar.no/acsys

(3) The US Global Change Research Program
http://www.gcdis.usgcrp.gov

(4) The Arctic Environmental Data Center of the University of Cambridge, UK
http://www.spri.cam.ac.uk/aemc/aemc.htm

(5) The Master Environmental Library (MEL) of the Department of Defense
http://mel.dmso.mil

(6) Arctic Scientific and Technical Information System (ASTIS), Calgary University, Canada
http://www.aina.ucalgary.ca/astis

[3] "Arctic Ocean Science from Submarines," report based on the SCICEX 2000 Workshop, April 1999, available at http://psc.apl.washington.edu/scicex/scicex2000.html.
[4] Private communication, Dr. Drew Rothrock, APL–University of Washington. About 15 percent of the potential U.S. Navy declassified upward-looking sonar data has been processed to date, in conjunction with the Arctic Submarine Lab in SD, and further processing is in progress.

Table E.1 Summary of Available Arctic Oceanographic Databases

Platforms / Measurements	Submarines	Surface Ships	Satellites	Buoys	Human Stations	Aircraft
Bathymetry	4,5,6	1,4,6	4	1,4	1,4	*
Temperature/ Salinity	5,6	1,3,6	3,6	1,3,6	1,3	6
Current	5,6	1,4,6	4,6	1,3,6	1	*
Ice Extent	*	2,3,6	2,3,6	2,3	3	2,6
Ice Draft	3,5,6,7	*	6	*	3	*
Chemistry	3,5,6	3, 6	*	*	3, 6	6
Biologics	5,6	3, 4	*	*	3	*
Sediments/ Minerals	*	4,6	*	6	6	6

Table Entry Descriptions

(1) Name: Joint U.S.-Russian Atlas of the Arctic Ocean
Organization: Environmental Working Group, Gore-Chernomyrdin Commission
Contents: Temperature, Salinity, Bathymetry (visual), Currents (visual)
Dates: 1948–1993.
Platforms: Ice camps, icebreakers, drifting buoys, surface ships
Source: Downloadable from: http://www.nnic.noaa.gov/atlas

(2) Name: Arctic sea ice extent and related products
Organization: National/Naval Ice Center
Contents: Charts and lat/long of sea ice extent, and ice model predictions
Dates: current, since 1996
Platforms: Satellite, aircraft, surface ships, buoys
Source: Downloadable from: http://www.natice.noaa.gov

(3) Name: NSIDC Data Catalog
Organization: National Snow and Ice Data Center
Contents: Comprehensive collection of remote sensing and in situ measurements from various platforms over entire Arctic region
(also contains links to EWG, NGDC, and SCICEX data)
Dates: historical and continuing
Platforms: various
Source: Downloadable from:
http://www.nsidc.colorado.edu/NSIDC/CATALOG/index.html

(4) Name: NGDC Data Catalog
Organization: National Geophysical Data Center
Contents: Comprehensive collection of remote sensing and in situ measurements from various platforms over entire Arctic region
Includes or links to bathymetry, hydrography, minerals, fish, paleoclimatology, gravity, and magnetics
Dates: historical and continuing
Platforms: various, including submarines
Source: Downloadable from: http://www.ngdc.noaa.gov/ngdc.html

(5) Name: SCICEX Data Sets
Organization: Lamont-Doherty Earth Observatory, Columbia Univ.
Contents: Non-comprehensive Arctic data set of in situ and acoustic measurements from U.S. Navy SCICEX submarine cruises.
Includes bathymetry, hydrography, chemistry, biology, ice draft, gravity, and acoustics of sections of the Arctic
Dates: 1993–1999
Platforms: nuclear submarine
Source: Downloadable from: http://www.ldeo.columbia.edu/scicex

(6) Name: NASA Global Change Master Directory
Organization: NASA
Contents: Central site with large number of links to U.S. and International databases about Arctic. Many physical parameters represented for one or more platforms in some region.
Dates: historical and continuing
Platforms: various
Source: Downloadable from: http://gcmd.gsfc.nasa.gov

(7) Name: Upward Looking Sonar for Ice Draft
Organization: Various
Contents: Additional data sets of upward-looking sonar to measure Arctic ice draft are available from several sources:
(1) see LeSchack, L.A., Tech. Report to ONR contract N00014-76-C-0757/NR 307-374
(2) see McLaren, A.S., J. Geophys. Res. 94 (1989) p. 4971.
(3) NSIDC will receive additional declassified data starting in calendar year 2000.
Dates: 1958–present
Platforms: nuclear submarine

Appendix F: Potential Treaty Limitations on a Scientific Submarine in the Antarctic

As noted briefly in Chapter 4, there is potential scientific value in using a submarine to conduct oceanographic and geophysical research in the oceans surrounding Antarctica. Scientific studies, and exploration in general, of this region are scarce and have been historically hampered by the region's remoteness and extreme weather conditions. The physical conditions in the seas surrounding Antarctica are in fact so hazardous that large areas are bathymetrically uncharted, and even the location of the continental margin is unknown in places. Operation of surface research vessels is often restricted to only a few months per year. While it would be feasible for a SSN 637-class submarine to operate in these waters, we have not considered the potential scientific benefits of Antarctic missions because of potential limitations associated with the Antarctic Treaty.

International activity in the Antarctic region is subject to the Antarctic Treaty and related law.[1] The Antarctic treaty, its regulatory measures, and subsequent international agreements on seals, fisheries, and conservation constitute what is informally called the Antarctic Treaty System. The Antarctic Treaty, signed in Washington, D.C., in 1959 by twelve countries including the United States, grew out of the political momentum of international scientific cooperation in Antarctica initiated by the United Nation's International Geophysical Year of 1957–58. The Antarctic Treaty's primary aims are to insure that the Antarctic continent is to be used solely for peaceful purposes, to promote international scientific cooperation in the area, and to stabilize the area politically by precluding actions for or against territorial claims. The Antarctic Treaty applies to the physical area south of 60°S latitude, known as the Antarctic Treaty Area, which includes all land areas and ice shelves. The Antarctic Treaty specifically prohibits activities of a military nature in the Area, except for military logistical support of open, non-military science and other peaceful purposes. The Antarctic Treaty and related law are restrictive in several ways as to the use of military hardware.

With respect to possible conduct of scientific activity using a nuclear-powered submarine, the Antarctic Treaty and its amended Consultative Measures constitute the principal, applicable international law distinctive to the Area. The Antarctic Treaty's 12 original signatories and the many more acceding states that are active in the Area are termed Consultative Parties, who meet from time to time to recommend Measures in furtherance of the Treaty. As of 1998, there were a total of 27 Consultative Parties nations, consisting of Argentina, Australia, Belgium, Brazil, Bulgaria, Chile, China, Ecuador, Finland, France, Germany, India, Italy, Japan, the Republic of Korea, Netherlands, New Zealand, Norway, Peru, Poland, Russia, South Africa, Spain, Sweden, the United Kingdom, Uruguay, and the United States. Seventeen more states have acceded to the Treaty but are not Consultative Parties, and hence are non-voting members. The Consultative Measures are recommended by consensus and become

[1]Many legal details in this section were elucidated for us in private communications by Gerald Schatz, to whom we are very grateful. Further details on the Antarctic Treaty can be found in his article in *International Legal Materials*, V. 35, No. 5 (Sept. 1996) p. 165.

binding upon unanimous approval by the states that were eligible to attend the Consultative Meeting that recommended them. The Antarctic Treaty has no secretariat, but the U.S. Department of State is the depository for the treaty documents, and does distribute information regarding it. There is no international organization to enforce the Antarctic Treaty per se, rather each signatory country must write and enforce its own laws to implement the treaties.

Of the original articles of the Antarctic Treaty, Article I explicitly prohibits the conduct of any military operations within the Area; however, the use of military personnel or equipment "for scientific or any other peaceful purpose" is explicitly allowed. In addition, Article V prohibits "all nuclear explosions in Antarctica and disposal of radioactive waste." U.S. submarines do not discharge radioactive wastes at sea; hence, operation of a nuclear-powered submarine would not be directly prohibited by the treaty.

However, there exist several additional Measures that may have national security consequences for a U.S. Navy nuclear submarine operating in this region. To be specific, Article VII states that "all areas of Antarctica, including all stations, installations and equipment, and all ships...at points of discharging or embarking cargoes or personnel, shall be open at all times to inspection" by international observers. Under the Treaty, any of the Consultative Party nations may appoint observers which have complete freedom to inspect any region or equipment within the Area. Other articles and measures that pertain in this regard are:

> Article VII, paragraph 5, which requires "advance notice of all expeditions to and within the Antarctic Treaty Area on the part of its ships or nationals and....of any military personnel or equipment intended to be introduced into Antarctica."

> Consultative Measure I-VI, which requires the international exchange of information regarding any military equipment to be introduced into Antarctica, including "names, types, numbers, description, and armaments of ships."

> Consultative Measure I-XIII, which requires the international exchange of information regarding the "application of nuclear equipment and techniques in the Antarctic Treaty Area."

The most direct effect of these regulations would be that putting to port within Antarctica proper would leave the submarine open to international inspection. In addition, open seas operation within the Antarctic Treaty Area would likely require a detailed disclosure of the submarine's mission, equipment, personnel, and armament. These points could create a serious issue for submarine operations, since the U.S. Navy may view such inspections as a potential security risk. Similarly the disclosure of such information as technical or design specifications would need to be carefully considered.

Providing that SSN 686 would avoid putting to port in Antarctica proper, operations in the seas surrounding the continent could also pose similar issues, not only with regard to potential inspections, but also with respect to international consent. For example, the ice shelves (and the ocean and sea bottom beneath) are considered as land mass for the purposes of the Treaty, hence use of the submarine for ice draft surveying could potentially leave it open to inspection. In addition, even more complicated issues arise with regard to operation in the territorial seas surrounding Antarctica. Article VI of the Antarctic Treaty states that "nothing in the Treaty shall affect the rights, or exercise of the rights, of any state under international law with regard to the high seas within that area." Hence, operations in the surrounding oceans must make reference to the legal regime defined by the international treaties regarding the Law of the Sea (LoS). Unfortunately, this treaty itself is not entirely without ambiguity, specifically with regard to marine scientific activities.

A very useful discussion of the interaction between the Law of the Sea and the Antarctic Treaty is given by Oxman.[2] The Third United Nations Convention on the Law of the Sea (1982) established a new legal regime for regulating maritime operations, which has for the most part been internationally accepted. In essence, this treaty established three different regulatory areas for the oceans: a Territorial Sea, which may be established by any government of a coastal state and extends from its land area into neighboring ocean out to a distance of 12 nautical miles; the Exclusive Economic Zone, which a government may establish out to a distance of 200 miles; and the "High Seas," which are areas of the world's oceans not included in either of the above. These three areas incur differing rights and responsibilities for both the coastal states and international maritime traffic within them. The Territorial Sea is, in effect, treated as part of the originating coastal state's land area, and the state has complete authority to regulate marine activity, except for the "right of free passage" of innocent traffic. While navigation through an area is considered innocent passage, marine scientific research is specifically not categorized as such. Within the Exclusive Economic Zone, the limits of state authority are still somewhat disputed internationally,[3] however, for the most part, high seas freedoms exist throughout, except that marine scientific research may be explicitly denied by the owning coastal state (and permission must be requested at least six months beforehand). Research operations within the high seas are for the most part unregulated, except for various environmental restrictions and a vague restriction that the "seas be used for peaceful purposes."

With respect to operation of a nuclear-powered submarine within this legal regime, a principal question is whether the right to claim a Territorial Sea or Exclusive Economic Zone even exists in the Antarctic region. Various countries now assert claims to portions of Antarctica, and those states could potentially assert restrictions to operations within their own respective Territorial Sea and Exclusive Economic Zones; however, Oxman asserts that these individual claims likely could not hold up to international pressure. More acceptable from the viewpoint of international law would be a joint action on the part of all Consultative Parties in the Treaty Area to assert regulation. However, enforcing this jurisdiction in practice would require a collective action on the part of the Consultative Parties, an action that would likely require considerable time and effort from a negotiations standpoint. Additionally, such joint action would be bound by the Articles of the Antarctic Treaty, which freely permits scientific activity, under the restriction of disclosure and potential inspection. Oxman's view is that the Antarctic Treaty indeed applies to a collective Territorial Sea and Exclusive Economic Zone, i.e. "in principal, the Treaty applies to areas of coastal state jurisdiction." Therefore, if such joint action were achieved, the Consultative Parties could require onboard inspections of the submarine in both the Territorial Sea and Exclusive Economic Zone surrounding all of Antarctica.

An even more controversial point with regards to the general operation of a submarine would be its classification as either a civilian scientific mission or military survey mission. Under the LoS, civilian

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[2]Oxman, Bernard "Antarctica and the New Law of the Sea," V. 19, *Cornell Intern. Law J.* (1986) p. 211.
[3]Mahmoudi, Said "Foreign Military Activities in the Swedish Economic Zone" *Intern. J. of Marine and Coastal Law*, V. 11, No. 3 (1996) p. 365.

research vessels and military survey vessels are treated somewhat differently with regard to disclosure and right of passage. Civilian vessels conducting marine scientific research in either a Territorial Sea or Exclusive Economic Zone are required to request permission from the coastal state under authority to do so; and the latter may deny this.[4] Generally, since 1983 the United States has requested permission from coastal states to perform civilian marine scientific research through its diplomatic channels. The case of military vessels conducting potential survey research is much more controversial, and in theory may be unlawful depending on the interpretation of the LoS by the individual coastal state. However, the United States has historically not asked permission for such activities by its military vessels, and in fact a variety of international disputes have arisen because of this. Within the Antarctic Treaty Area, the perception of the nuclear-powered submarine as a military research vessel could in fact be argued to violate the "peaceful purposes" measures, and result in joint action by the Consultative Parties to deny access.

It is important to note that most of the above restrictions with regard to the LoS carry over into ocean areas worldwide. In fact, without the guarantee of freedom of scientific research provided for by the Antarctic Treaty, the regulation of civilian research activities by the submarine in foreign Territorial Sea or Exclusive Economic Zone becomes even more restrictive. In such areas, LoS Article 249 allows coastal states the right to refuse access altogether or otherwise require participation by coastal state scientists, to have free access to any data generated by such activities, to provide assistance in interpreting collected data, and generally to allow the participation of the coastal state in the project. On the other hand, operation of the submarine in accordance with the historical precedence of U.S. military vessels would implicate its mission as being military in nature. While the application of LoS restrictions to research conducted by warships is controversial, the potential political ramifications of conducting marine survey research by military vessels are even more severe.

Although many legal aspects of operating a nuclear-powered submarine in the Antarctic Treaty Area could be debated, clearly the larger international political consequences of doing so should take precedence. A primary aim of the Antarctic Treaty has been to reconcile or sidestep altogether the complicated network of conflicting territorial claims in the Antarctic, which are potentially inflammatory. The operation of a nuclear-powered submarine in this region, as discussed above, could put to test some of these compromises. Obviously, it would not be in the best interest of the United States to perform purely scientific operations in a fashion that would precipitate international discord or distrust. A surprising number of potential controversies could be involved in the Antarctic region, deriving from such diverse sources as: any U.S.-New Zealand understanding concerning nuclear and naval issues; potential objections by Russia concerning introduction of a U.S. nuclear warship into the Antarctic Treaty Area; similar objections by third-world nations, particularly India; and reaction in the United States and abroad by Greenpeace and allied organizations.

Worldwide operation of the submarine in Territorial Sea or Exclusive Economic Zones has similar potential for political conflicts. According to Douglas Brubaker of the Fridtjof Nansen Institute,[5] additional issues in these areas include: the international perception that the mission of the submarine

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[4]J. Ashley Roach, "Marine Scientific Research and the Law of the Sea," *Ocean Development and Intern. Law*, V. 27 (1996) p. 59.
[5]Douglas Brubaker, private communication.

would be primarily military; the general controversy that arises whenever a nuclear-powered vessel comes to a foreign port and the special agreements required between parties; the issues of liability and compensation that arise because of a potential nuclear accident when operating in foreign territorial waters; and the fact that an SSN 637-class submarine could cause more than usual concern.

The extent of such concerns over the operations of a dedicated scientific submarine in the Antarctic could possibly lessen after several years of favorable international experience with operations in the Arctic. Nonetheless, in attempting to avoid potential complications, transparency of motives and mission objectives would be a prudent guideline for the Antarctic operations of SSN 686. Prior and full disclosure to the international community of equipment, crew, and operational plans, even to the extent of limited inspection, would do much to allay any potential controversy. The inclusion of scientists or scientific equipment from the international community on a routine basis may also reduce concerns from other nations. Whether or not this would create an unacceptable security risk to the U.S. Navy would then have to be considered as part of the potential risks and benefits of operating a nuclear-powered submarine for unclassified research throughout the world's oceans.