UNIVERSITY - NATIONAL OCEANOGRAPHIC LABORATORY SYSTEM

SUBMERSIBLE SCIENCE STUDY
FOR THE 1990's

By A
Submersible Science Committee
of the
University-National Oceanographic Laboratories System

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REPORT OF THE SUBMERSIBLE SCIENCE STUDY COMMITTEE

PREFACE

The present Submersible Science Study was initiated in May, 1986 by a charge from the UNOLS membership to the ALVIN Review Committee to draft a plan for conducting a study of the broad scientific program requirements for submersibles and related technologies in the next decade and beyond. In August, 1987 a subcontract was issued by the UNOLS Office through the University of Washington, to the University of California at Santa Barbara's Marine Science Institute, to conduct the study. The study was supported through funds from NOAA, NSF and ONR, administered under NSF grant number OCE-8500868.

The committee work for the study was conducted at three meetings: the first in Santa Barbara, CA in September, 1987; the second in Kingston, RI in March, 1988; and the third in Monterey, CA in June, 1988. Most of the work for the study was accomplished individually or by groups of two or three committee members addressing specific issues.

The study was focused on two principal objectives:

- To assess the trends, patterns, and directions for academically-based ocean science research programs that can best be served by submersible systems, both manned and unmanned. This assessment was to cover the full range of depth requirements needed by the science.
- To develop a comprehensive submersible science facilities plan which satisfies the science requirements identified above, including the rationale for such facilities, and possible funding and management arrangements.

The members of the present Submersible Science Study Committee include:

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The conclusions and recommendations in this report represent the concensus of the entire committee. However, individual opinions vary and certain portions of this report do not necessarily reflect the views of every committee member.

The committee gratefully acknowledges the advice and assistance of: Bill Barbee (UNOLS); Shanna Bowers (UCSB); Marie Ciluaga (UCSB); James J. Childress (UCSB); H.L. Clark (NSF); Robert W. Corell (NSF); David Duane (NOAA); Sylvia Earle (DOT); J. Edmond (MIT); Jim English (CAN-DIVE); Steve Etchemendy (MBARI); P.J. Fox (URI); W.M. Hamner (UCLA): G.R. Harbison (WHOI); Graham Hawkes (DOE); Feenan Jennings (TAMU); Al Kalvaitis (NOAA); Keith Kaulum (ONR); George Keller (OSU); Mike Lee (MBARI); J.R. McFarlane (ISE); L.P. Madin (WHOI); Kim Reisenbichler (MBARI); Lt. George Rey (USN); W.B.F. Ryan (L-DGO); K.L. Smith, Jr (SIO); Allyn C. Vine (WHOI); Barrie Walden (WHOI); M.J. Youngbluth (HBOI); and in particular, we thank Lynne Carter Hanson (URI) for her considerable efforts on our behalf and for her contributions as a participant in several of the committee's discussions. We also acknowledge the important contributions of the Monterey Bay Aquarium Research Institute (MBARI) to the content and conduct of the study.

SUBMERSIBLE SCIENCE STUDY

EXECUTIVE SUMMARY

The Submersible Science Study is a long-range planning effort, designed to assess the role of submersibles in oceanographic research during the 1990's and beyond. It takes the user's perspective in analyzing research trends to project the oceanographic community's needs for submersible facilities over the next 10-15 years. The term submersible is used broadly here to include both manned vehicles as well as unmanned systems.

The principal problem confronting the research community is lack of access to submersible systems. These will be primary tools of the next generation of oceanographers; yet while the technology continues to evolve, the development of research methodologies for their utilization is lagging far behind. Thus the challenge to UNOLS and to the federal agencies which are the primary supporters of oceanographic research, is to develop the means for providing access to these essential facilities. While there has been some recent progress along this line, the overall situation is not good and the majority of researchers are very poorly served through the existing programs.

The goal over the course of this study has been to facilitate science by exploring the means for making the necessary tools readily available to the research community. For nearly two decades UNOLS has served the community by facilitating access to research vessels; UNOLS works and it works well. As a consequence, we have framed our recommendations to fit within this successful framework in order to create the least amount of new bureaucracy, and to provide a cost-effective and realistic plan that can be readily implemented.

SCIENTIFIC DEMAND

We can confidently predict that the demand for submersible systems, both manned and unmanned, shallow and deep, will continue to expand through the next decade. At the present time, demand far exceeds availability, but because there is no mechanism for making this technology readily available to the majority of the research community, these needs, and as a consequence, the natural evolution of scientific progress, are being stifled.

Given a suitable means for providing access, we believe that by mid-decade the annual demand for submersible systems for funded research projects will be at about the following levels:

- continued full utilization of ALVIN,
- 100+ days of time on manned vehicles capable of reaching 6 km, ramping up to a full year of use by the end of the decade,
- 850 days of time aboard single- and multi-seat manned submersibles operating to depths of about 1 km,
- 600 days of time using deep-diving (2-5 km), general purpose, unmanned ROVs, and
- 1,000 - 1,500 operational days for small, shallow, low cost ROV's.

Submersible systems will be needed by all of the federal ocean research agencies for both their core research programs, as well as for their projected global scale programs. However, these levels of utilization will not require large, short-term capital investments in facilities. Most of the submersible systems necessary to meet these needs are already at hand. Biology and geology will be the disciplines most requiring these facilities, at least for the first half of the decade. Chemical oceanography needs will be intermediate and needs for physical oceanography will probably ramp up the slowest. This demand is very real and very strong. These needs will greatly exceed our present federal facilities and our organizational capabilities to deal with them. Given access to the needed facilities, by the end of the decade, submersible systems will become the standard oceanographic technology for work in the water column and on the sea floor. Eventually, submersible technology will surpass satellites as a source of primary oceanographic data.

Today there is a broad range of submersible systems potentially available. This is a rapidly evolving technology and thus research capabilities are expanding. The core technologies which are driving this expansion are usually coupled to industrial and military R&D and have been only secondarily applied to submersibles or for ocean research. These technologies include: robotics, fiber optics, high-level data management, exotic imaging systems and sensors, and precision subsurface navigation.

Submersible technology encompasses both manned and unmanned systems. Each approach has its strengths and its disadvantages -- both kinds of systems are absolutely essential for the development of submersible science.

A good variety of submersible systems is available by commercial lease. Both new and used vehicles are also available for sale. There are four basic categories of vehicle to be found -- tethered and untethered, manned and unmanned. To date, most research use has been conducted with tethered unmanned systems and with untethered manned systems. For the near-term, these two categories will probably continue to dominate scientific usage. By the end of the decade, autonomous unmanned vehicles will perform a large number of research functions.

Most of the contractors who lease submersible systems commercially are reliable, and they strive to meet their clients' needs with the best hardware available. However, there are a few outmoded or poorly maintained vehicles that some contractors will supply to unwary clients. It is necessary to do one's homework when contracting for a leased vehicle (or to establish a UNOLS committee to do it for the community), to ensure safety and reliability.

Our recommendations for providing research access to submersible systems for the next decade fall into four categories:

- improvements to the ALVIN program,
- gaining access to depths beyond 4 km,
- providing shallow depth vehicles on a scale to meet demand, and
- establishing a permanent submersible science committee.

ALVIN

The ALVIN program gets high marks for providing a safe and effective tool for deep-sea research. ALVIN's effectiveness has been greatly enhanced by its conversion to a single point lift, by the replacement of LULU with the ATLANTIS II, and by its new control and propulsion systems. Likewise, recent changes in personnel policies for pilots and technicians are an appropriate first step to help reduce the rapid turnover problems that have periodically hampered the program. However, there are continuing needs for technological improvements and crew expansion in order to raise the efficiency of the system to meet the scientific and technical demands that will be placed on it over the next 10-15 years.

Among ALVIN users there is widespread dissatisfaction with the suite of tools, instruments, cameras and lights that are presently available. The consensus is that in most cases these assets are obsolete and are often unreliable. The next major effort should be to upgrade these subsystems to match the quality and dependability of the primary system.

Of particular concern have been data logging, video systems, sonar systems, navigation, and Seabeam. Seabeam data acquisitions should be a standard function during most ALVIN operations (and thus not borne as costs to research grants). However, the data processing costs should continue to be supported by individual grants. The committee also believes that ALVIN should be equipped with an integrated, real-time navigation and high resolution, scanning sonar system. There is a need as well, for greater reliability in the datalogging system. Lastly, the video imaging and lighting systems are seriously inadequate and far below current state-of-the-art for underwater applications. These systems require immediate upgrading.

GAINING RESEARCH ACCESS TO DEPTHS BEYOND 4,000 METERS

One of the principal recommendations of the Jennings Committee Report "New Directions for NOAA's Undersea Research Program" (1986), was that the U.S. must extend its deep diving research capability through the development of a 6 - 7,000 m submersible by the mid-1990's and a 10,000 m vehicle by the end of the century. The only operational 6 km submersible in the U.S. is the Navy's Deep Submergence Vehicle SEA CLIFF. To date, SEA CLIFF has been available to the civilian research community only on a very restricted basis.

The potential for improving this situation has recently changed for the better with the acquisition and refitting of a leased support vessel, the M/V LANEY CHOUEST. Likewise, directives from the Secretary of the Navy have made a limited provision (up to 60 days/year) for civilian research utilization of SEA CLIFF (and its shallower counterpart TURTLE). These changes reflect a new attitude of cooperation with the civilian research community by the Navy's Deep Submergence Systems Division (OP23). Despite this welcome improvement, the program has yet to be fully organized and put into practice on a regular basis. Even with this new commitment, there is a growing feeling among U.S. scientists that at best, SEA CLIFF offers only a stop-gap solution for the problem of providing deep seabed research access in the 1990's and beyond, because of temporal and geographical operational restrictions, and limited availability. However, the demand for access for depth greater than 4 km will soon surpass what SEA CLIFF can offer.

At the present time, there are only five operational submersibles in the world capable of reaching a depth of 6 km:

- SEA CLIFF (U.S. Navy, DSV-4) was built in 1968 with the same general configuration and operational capabilities as ALVIN (DSV-2). In 1983, its original personnel sphere was replaced with a titanium one to give it an operating depth of 6 km. It is operated by the U.S. Navy and in the last decade has been only occasionally available for civilian research use; it has not been operated consistently in the 4-6 km depth range, although it is annually re-certified to these depths. It has not yet had an effective impact on the needs of the academic research community.

- NAUTILE (French) was launched in 1985 by IFREMER for commercial applications as well as for research. It holds a crew of three in a titanium personnel sphere with an operational depth of 6 km. It has been used by several U.S. scientists working in cooperation with French investigators. It is also available for lease with its support vessel NADIR. NAUTILE carries state-of-the-art video and photographic systems, as well as advanced sonar systems, manipulators and instrumentation. NAUTILE has been operated successfully and continuously in the 4-6 km depth range. IFREMER is presently planning the construction of a second NAUTILE-type vehicle.

- MIR I and MIR II (Russian). In December of 1987, two 6 km research submersibles were launched by the Finnish Company, Rauma-Repola. Both vehicles were delivered to the Soviet Academy of Sciences. They are twice as fast as any other deep submersible (5 kts), with twice the battery power, and a steel alloy sphere that holds a crew of three. Both have paired manipulators and a full set of tools and precision instrumentation. Both of these submersibles are deployed from the dedicated support vessel AKADEMIK KELDYSH. They are available for lease or on a cooperative exchange basis. Operations in U.S. waters are scheduled for 1990.
- A fifth deep research submersible, Japan's SHINKAI 6500, was completed in 1989 and is presently operational. It has a titanium sphere, a crew of three, and is the deepest diving manned submersible in operation. Built by Mitsubishi, it is deployed from the dedicated support vessel YOKOSUKA. In addition, SHINKAI's operator JAMSTEC, has begun the development of an unmanned vehicle capable of reaching 10 km depth.

ALVIN's 4 km depth range has brought roughly half of the world's benthic regions within the reach of U.S. researchers. A 6 km depth range nearly doubles the coverage, such that about 98% of the sea bed is accessible. The regions of the sea floor that are beyond ALVIN's reach include the deeper portions of continental margins, deep sea trench slopes and floors, deep ridge crests and many ridge flanks, transform fault zones and fracture zones, and the abyssal plains.

At present, the demand by U.S. scientists for 6 km research capabilities is limited by artificial constraints. Researchers with interests in oceanographic processes or benthic features that extend beyond ALVIN's 4 km depth range know that their chances of ever getting dives to those depths are negligible. As a consequence, investigators are not willing to waste their time in requesting this type of facilities support. This is not to say that there is no good science to be carried out in the 4-6 km depth range; rather, U.S. scientists do not presently have any reliable access to 4-6 km manned submersible facilities. Emerging unmanned systems may have substantial near-term impact on some scientific requirements. Systems like ARGO/JASON, RUM III and HYSUB are securing a niche at depths up to 6 km for research which does not require manned presence.

Given the scientific justification and the growing need for deeper access, there are several possible ways to proceed:

Option 1. Expand and improve civilian research access to SEA CLIFF.

Option 2. Lease option for foreign flag submersibles.

Option 3. Rebuild TURTLE to extend its range from 4 to 6 km.

Option 4. New construction of a conventional 6 km manned vehicle.

Option 5. Alternative technologies.

Option 6. Unmanned systems.

One way to gain deep-sea access and to push the evolution of appropriate technologies would be to develop a new generation of deep diving, unmanned submersibles. Such a vehicle could be battery powered to eliminate the many constraints imposed by tethers which supply power from the surface. Improved power/weight ratios from new kinds of batteries and reduced power demands without life support requirements, make a self-powered vehicle a practical option. At the same time, a limited degree of real-time control and data acquisition can be maintained with fiber optic links or with pulsed acoustic links. These are areas where U.S. technology can make a real contribution because of its particular engineering strengths in communications, robotics and high level control. Areas that will require development but where breakthroughs are near, include batteries, telemetry and instrumentation, and pressurized electronics.

There are several advantages to this approach. We would gain limited-capability access to the deep-sea floor for less than half the cost of a conventional manned vehicle. The operating costs would also be reduced. Because of its smaller size, there would be no need for a dedicated support vessel. Instead, the vehicle could be deployed from a number of our larger research vessels. Unmanned, untethered systems can be surface-controlled and can send crude, real-time imagery over fiber optics or acoustic links. As a rule, they can carry more sensors, are safer, smaller, and more easily deployed than manned subs. They can be "tuned" to be optimized for applications requiring greater speed, more payload, unobtrusiveness, or longer mission times far more readily than conventional manned subs.

Non-conventional manned vehicles also offer real promise for achieving maximum depth research capabilities. In concept, such vehicles take advantage of all of the technologies mentioned above for unmanned systems. They differ only in adding self-contained personnel capsules. In this approach only the capsules need be man-rated for operational depths. This approach offers the considerable advantages of human intervention and full real-time control, without the large size and complexities associated with conventional manned vehicles. It is reasonable to consider the sequential development of a deep-diving system which first operates remotely as proof-of-concept, then incorporates manned capabilities with the addition of deep-rated personnel capsules.

Given the logical priorities of the Navy's deep submersible program and the limited prospects for utilization beyond 60 days per year by the civilian science community, it is difficult to be optimistic about SEA CLIFF meeting the growing needs of civilian research in the 1990's. We support the recommendation of the Jennings Committee that the U.S. should not delay in its development of a 6-10 km research diving capability. However, since that recommendation has been virtually ignored by NSF, ONR and NOAA, we believe that the best approach in the current funding climate would be to: (1) encourage the Navy and other U.S. funding agencies to continue to commit at least 60 days of SEA CLIFF time annually for U.S. civilian scientists; (2) when the needs for deep access exceed SEA CLIFF's available time or capabilities, foreign submersibles should be leased for U.S. science in the 4-6 km depth range; and (3) initiate immediately the phased development of an unmanned/manned system that would promote state-of-the-art technological development and access to the greatest ocean depths (10 km).

In these circumstances, the question of the effectiveness of manned systems vs unmanned systems is again not an issue. For work at depths beyond 4 km, manned systems are inherently much more capable and flexible, albeit more expensive. Within the operational limits of unmanned systems however, some of our preliminary deep benthic research needs can be met. If the U.S. were to successfully develop such an unmanned vehicle, our deep manned submersible needs for the 1990's might be met by trading time on our unmanned system for time in foreign manned vehicles. Then manned access to the greatest depths could follow, with the second phase of development.

PROVIDING ACCESS TO SHALLOW DEPTH VEHICLES

With regard to vehicles operating at depths of about 1 km or less, the committee believes that leasing is the most cost-effective approach (although one UNOLS member already has such equipment as institutional assets).

The development of technology to work at moderate depths in the ocean has occurred largely in the private sector, to meet the needs of the offshore oil industry. Only in recent years has the scientific community begun to use these tools. The results have been strongly positive and demand for access to them is growing rapidly. The two principal impediments to using this equipment in grant supported projects have been the difficulties of (1) surviving the peer review process when the costs of contracting for the submersible must be included as line items in proposed research budgets and (2) dealing with two separate programs -- one for research support and the other for facilities support. There are no established procedures within NSF, ONR or NOAA to make the contracting process as straightforward as the scheduling of a UNOLS ship. This situation must be changed and the three agencies should work together to facilitate the change.

The NOAA/National Undersea Research Program (NURP) Center at University of Connecticut, Avery Point has repeatedly demonstrated the value of the leasing concept to provide NOAA researchers with access to specialized submersible research facilities. Recently, the center at the University of North Carolina, Wilmington, and (until 1990) the Fairleigh-Dickinson University Center at St. Croix, have followed suit. The principal problem with the national (NURP) program is that West Coast researchers are virtually disenfranchised, with no real regional program and thus no effective access to these facilities. While the national office has begun to deal with this problem, lack of funding has prevented a solution. This situation is a major flaw of the program which urgently requires corrective action by NOAA and its parent, the Department of Commerce. Dealing with this situation should involve NSF and ONR, as well as NOAA, with the goal of increasing overall federal support and developing inter-program support mechanisms such as UNOLS. At the present time there is no effective coordination between NSF, ONR and NOAA/NURP in this regard.

To deal with the problems of providing access to shallow depth vehicles, the committee makes the following recommendations, which follow closely the current procedures of each agency, and call for little or no re-organization.

At ONR, submersible contract costs should be budget line items, just as ship costs are handled now. Oversight of contracts, safety standards and insurance would be handled by a UNOLS Submersible Science Committee.

At NSF, requests for submersible facilities support should also be handled like that agency's ship time requests. Research proposals should contain facilities requests like the 831 form for ship time, with details on the specific system requirements. Contracts for submersible systems would be funded by OCFS through an appropriate UNOLS ship operating institution (or through NOAA/NURP), again with oversight to strict safety and operational standards by a UNOLS Submersible Science Committee.

NOAA's Undersea Research Programs are already well along in their development of leasing programs to meet the agency's needs. However, there is a critical need to provide geographic balance to the national program, first with the establishment of one or more functional West Coast Regional centers and then one on the Gulf Coast.

The committee also recommends that NOAA's NURP Centers should join UNOLS as full members, to bring their experience to the rest of the community and to become involved in scheduling and the setting of operational standards. Thirdly, the committee agrees with the recommendations of the Jennings Report that NURP should provide expanded support of research, as well as support for facilities. Finally, NURP should reconsider its misguided policy against the use of one-person submersibles.

In each of these cases, the principal investigator will not have to re-invent the wheel each time he or she needs a submersible to conduct research. Rather, support for submersible facilities could be handled matter-of-factly, like agency requests for ship time or other facilities -- and science will become the driving force -- not the facilities. The keystone of these recommendations is the creation of a new UNOLS committee, the Submersible Science Committee, to help meet the program needs of all three agencies.

ESTABLISHING A PERMANENT SUBMERSIBLE SCIENCE COMMITTEE

The most important recommendation of this report concerns the continuing need for the kind of effort that this committee has conducted. In order to implement the present committee's findings and to facilitate the integration of submersibles other than ALVIN into the oceanographic research community, there is a clear need for a permanent Submersible Science Committee (SSC) within UNOLS. In our view, the most appropriate action would be to make the SSC a sister committee to the ALVIN Review Committee. Such a group should be established as soon as possible.

The role of the UNOLS Submersible Science Committee would include:

- establishing guidelines and providing oversight for contracting, safety, and insurance for leased submersible systems,
- establishing basic operational standards for leased and owned systems,
- coordinating and promoting the efficient joint scheduling of ships and submersibles on an inter-agency basis,
- assisting the Navy in developing effective user programs for SEA CLIFF and TURTLE, and
- monitoring and promoting the development and application of appropriate new technologies for submersible science.

PRINCIPAL RECOMMENDATIONS OF THE SUBMERSIBLE SCIENCE STUDY COMMITTEE

1. ALVIN should significantly upgrade its tools, navigation, instrumentation and imaging subsystems, and continue to improve its personnel policies.
2. Development of technologies and programs should be initiated immediately to provide effective research access to depths beyond 4 km.
3. NSF and ONR should develop programs to facilitate the commercial leasing of submersibles. NOAA'S NURP program should establish a West coast regional program without delay. NOAA's regional NUR centers should join UNOLS.
4. UNOLS should establish a permanent Submersible Science Committee.

SUBMERSIBLE SCIENCE STUDY

INTRODUCTION

Ocean Science in the U.S. is experiencing the onset of a major technological transformation. This change involves the widespread use of submersible systems (both manned and unmanned) throughout the oceanographic research community. The only comparable developments in recent history have been the incorporation of earth-orbiting satellites as data collecting platforms and the commonplace use of computers at sea.

For the past 25 years the principal asset of this country's submersible-based oceanographic research programs has been the DSV ALVIN. Through 1986, three of every four publications by U.S. scientists based on data generated from submersibles, was an "ALVIN paper." Through continuous upgrading and two major alterations -- a titanium personnel sphere that extended its depth range from 2,000 to 4,000 m in 1973, and conversion to a single-point lift for deployment from the R/V ATLANTIS II in 1984 -- ALVIN has been excellent at doing what it was designed to do. What ALVIN does best is to work on the seafloor at depths between 1,000 and 4,000 m. As a consequence, the research areas most strongly supported by ALVIN over the last 25 years, have been seafloor geology, deep benthic biology and deep-sea vent chemistry.

ALVIN was built during the period between 1963 and 1968, when the U.S. Navy spent more than $83 million to construct five submersibles: ALVIN (DSV-2), TURTLE (DSV-3), SEA CLIFF (DSV-4), TRIESTE II, and NR-1. All but the bathyscaph TRIESTE are still operational. Two additional Navy vehicles, the Deep Submergence Rescue Vehicles MYSTIC (DSRV-1) and AVALON (DSRV-2), were initiated during this period but were not completed until 1970-1971. At one time or another all of these deep-diving vehicles have been used for research but, with the exception of ALVIN, their operations have been almost exclusively for military purposes.

In the late 1970's, elements of the civilian ocean research community developed plans for a large submersible vehicle to work the outer reaches of the continental shelf and the upper layers of the water column, using saturation diving as a means of access to these habitats. The concept, known as OCEANLAB, was not implemented. Instead, the OCEANLAB evolved into the present-day NOAA National Undersea Research Program (NURP).

NURP, designed principally to facilitate NOAA's research interests, has established four regional centers. The University of Connecticut and the University of North Carolina provide researchers with dive time on leased submersible systems and with owned, low-cost ROV's. Fairleigh-Dickinson University operated the saturation diving habitat AQUARIUS at St. Croix and also leased commercial systems for research support until the program was ended in 1990 (AQUARIUS is now operated by UNC). The University of Hawaii operates the PISCES V manned submersible and a small ROV system. There are no regional centers at institutions on the U.S. West coast or the Gulf coast. The NURP leasing program has proven to be a very successful approach within the constraints of NOAA's science missions and within NURP's limited geographical coverage. The last half of the 1980's saw an increase in the number of publications based on submersibles other than ALVIN, largely due to NURP's activities.

As the decade of the 1990's opens, the submersible facilities resources available to the ocean research community do not meet the needs of academic scientists. Our chief asset, ALVIN, has only limited capabilities for work in the water column and it badly needs a major upgrading of its tools, instrumentation, and subsystems. SEA CLIFF, our only 6 km submersible is potentially available at best for only 60 days each year (including transit) to do civilian science, and it too is in need of critical technical upgrading to carry out most scientific missions. NURP's principal operations and facilities are limited to the western North Atlantic and the waters around the Hawaiian Islands. Further, NURP's budget is far too small to support the submersible facilities needs of NOAA's own scientists, much less those whose research is funded by NSF or ONR. These latter agencies have no practical means for providing submersible facilities support to their principal investigators, except aboard ALVIN, or occasionally aboard SEA CLIFF, and NR-1.

For the scientist who needs submersible facilities to conduct his or her research, the challenges of gaining access to state-of-the-art technology are formidable. As a result, the rapid development of undersea technologies has far outpaced the development of research methods to utilize them. Submersible systems will be primary tools of the next generation of oceanographers, yet with a serious mismatch between technology and methodology, the evolutionary progress of research in this field will be seriously constrained. There is a growing need for an integrated approach by NSF, ONR, and NOAA to deal with this problem on a national level.

In 1981 these three agencies commissioned the first Submersible Science Study Committee, to "review the past, present and then predict the future requirements for a national technical facility which gives access to the ocean for submerged 'manned' vehicles." The 1982 S^3 Report contained a number of near-term and far-term recommendations. The chief recommendations, and indeed the only ones acted upon, concerned the conversion of ALVIN to a single-point lift and the replacement of its support vessel LULU with ATLANTIS II. Recommendations concerning future needs for additional submersible systems with characteristics and capabilities beyond ALVIN's have been largely ignored. The lack of action on issues beyond those affecting ALVIN reflects the fact that the ALVIN Review Committee is the only permanent inter-agency group which addresses the issue of submersible facilities support on a national level; and it deals only with ALVIN.

In 1985 and 1986 the NOAA-appointed Jennings Committee examined NOAA's role in meeting the nation's undersea research needs. The results of that study included a set of nine recommendations, seven of which dealt directly with issues concerning submersible-based research. However, because of administrative changes at NOAA and because the committee disbanded once its report was completed, no new action was taken to implement the results of the study.

In the present study we have examined the issues from the point of view of the working scientist. From that perspective it is clear that the greatest problem is the lack of access to submersible systems. Thus the most important step that we can advocate is the creation of new committee structure to deal with this problem on a continuing basis. A host of important multi-disciplinary scientific questions which require submersible technology, exist. The technology necessary to address these questions exists. What we lack are the ready means to get the required tools into the hands of the researchers.

The present study consists of five main parts: (1) An assessment of research trends with a projection of the oceanographic community's submersible needs during the decade of the 1990's; (2) An assessment of submersible capabilities and technological needs; (3) A discussion of strategies for gaining access to depths beyond the reach of ALVIN; (4) A discussion of strategies for providing research access to shallow depth (<1,000 m) vehicles; (5) And finally, recommendations for management and infrastructure changes to facilitate submersible science.

ASSESSMENT OF SCIENTIFIC NEEDS

What follows is a catalogue of research topics and investigative initiatives that will require the use of submersibles. This listing is by no means exhaustive or complete. However, it does serve to indicate the broad scope and fundamental importance of the submersible-based science that must be conducted during the decade of the 1990's. The assessment of scientific research topics is presented in three sections: the Deep Sea Floor; the Shelf and Upper Continental Shelf; and the Water Column. Each of these sections contains a subsection describing submersible capabilities required for each research category. These three sections are followed by a fourth, which presents the estimated levels of submersible utilization.

DEEP SEA FLOOR

The crest of the mid-ocean ridge (MOR) system lies generally at depths between 2500-3000 m, while the floors of many transform faults and trenches lie between 4000-7000 m. Seamount summits may occupy depths as shallow as 1000 m while their flanks descend to depths as great as 3000-4000 m. The deep sea floor encompasses a wide variety of volcanic as well as sediment covered terrains in tectonic settings that span the range from spreading ridge to subduction zone, and include endemic small- to large-scale structural and morphological features that reflect the geological processes at work within those environments.

The ongoing need for deep-diving manned submersibles and the continued development and use of ROV's is evident in all the near- and far-term oceanographic objectives that are dedicated to the investigation of deep sea floor problems. For example, the consensus of that part of the marine science community which has formulated a long-range plan to study the world's mid-ocean ridge (MOR) system, is that at least six months per year of ALVIN time, or the equivalent, will be needed during the next 8-12 years, to meet the interdisciplinary goals of the local-scale or seafloor experiments facet of the RIDGE program (Ocean Studies Board, 1988).

A large number of important scientific questions that address key problems concerning tectonic, volcanic, sedimentary, biological, and geochemical processes on the deep sea floor are currently being proposed for study. These will continue to be a principal focus for the submersible science effort in the coming decades. Areas of present and future study include:

MID-OCEAN RIDGES

The current view of the MOR is that it represents one of the earth's greatest physical, biological and chemical wonders: a world-encircling chain of volcanos and offsetting transform faults 70,000 km in length, where hydrothermal vents spew out 350°C mineral-rich waters and a unique ecosystem based on chemosynthetic organisms flourishes.

1. MOR SEGMENTATION, especially the nature and implications of ridge segmentation, and the driving forces that create the morpho-structural fabric of the ocean floor are key questions to be resolved on a global scale. In some cases fundamental seafloor spreading processes are manifested by small-scale features that can only be studied and measured through the use of near-bottom remote sensing vehicles (both acoustic and photo-imaging) and submersibles.

2. SOUTH AND SOUTHWEST PACIFIC MOR, SOUTH ATLANTIC AND INDIAN MOR's. We have only recently begun to explore that portion of the MOR system that lies beyond

the North Atlantic or eastern Pacific. Future studies of the MOR will include both reconnaissance and detailed observations of: fast-spreading ridges in the southern Pacific, back-arc spreading ridges in the western and southwestern Pacific, asymmetric spreading ridges in the Australian/Antarctic discordance zone, and medium-spreading-rate ridges in the Indian Ocean.

3. CHEMICAL AND BIOLOGICAL PROCESSES ALONG REMOTE SEGMENTS OF THE MOR SYSTEM. The potential for significant discoveries in chemical and biological processes along as yet unstudied and remote segments of the MOR cannot be understated. Given the importance of hydrothermal input to global ocean chemical fluxes and the dependence of vent-based biota on hydrothermal fluid composition, interdisciplinary studies of remote segments of the MOR will provide important constraints for understanding the global distribution of vent animals, the spatial systematics of vent chemistry, and the dependence of these deep processes on MOR magmatic cycles.

4. MOR DISCONTINUITIES. Propagating ridges have also been investigated in a very limited manner using submersibles. Remote-sensing studies in these environments have shown them to be very complex tectonically and volcanically. However, the study of seafloor structures that result from volcano-tectonic processes in these environments allows the spreading history to be reconstructed and offers hints at the mechanisms responsible for plate movement. Consequently, detailed field studies that require manned submersibles and ROV's will be needed to conduct site-specific sampling, to make visual observations and carry out near-bottom high-resolution sonar recording of small-scale tectonic and volcanic features in these types of environments. These kinds of studies are essential to the correct mapping and identification of small-scale features and to our understanding of how they integrate spatially to create the regional tectonic fabric of the deep seafloor.

TRANSFORM FAULTS, FACK-ARC BASINS, SEAMOUNTS, AND TRENCHES

The morphology and structure of the seafloor reflect to a great degree the volcanic and tectonic forces that shape it. The identification of ridge propagation, back-arc spreading and intraplate volcanism at various scales has revolutionized our understanding of how seafloor structures are created and the complexity of interactive tectonic processes. Only a few of these features have been investigated in detail; with an even smaller subset studied directly by submersible observations and sampling. Many of these features are present in depth ranges deeper than the current 4000 m capability of ALVIN, yet the scientific problems to be solved by in situ studies are compelling and will certainly be addressed in the next decade. The following list highlights some of the major scientific problems that may require submersible assets that can reach 4-6 km depths.

1. TRANSFORM FAULTS. ALVIN has only investigated a few transform faults with slip-rates in the low to medium range. Future submersible and ROV-based programs will be devoted to exploring the complex terrain developed at fast-slipping transform faults along the southern part of the East Pacific Rise. Some of the most structurally critical portions of these features lie at depths between 4000-6000 m. These areas are characterized by complex seafloor fabric, pull-apart basins that accommodate accretion within a transform domain, and strike-slip faulting. Visual observations and site-specific, in situ sampling are essential to solve some of the complex geologic, tectonic and petrologic problems in these areas.

2. INTRA-TRANSFORM SPREADING CENTERS. While much of the MOR crest lies at depths between 2500-3200 m, small segments of the MOR actually lie within broad transform domains in depths between 3500-5000 m. These short (5-30 km long) spreading centers are often present as narrow troughs or sigmoid-shaped pull-apart basins, separated by one or more transform faults that link them to major segments of the MOR

system. No near-bottom investigations of small spreading centers within transforms have been carried out. These environments will certainly be a focus of future submersible studies because the tectonic implications of accretion within a transform domain fundamentally alter our concepts of rigid plate boundary geometry and the processes responsible for creating upper crustal morphology and structure.

3. SEAMOUNTS. The tops and flanks of seamounts lie well within the depth of operation of ALVIN, but few have been investigated. Shallow internal structure beneath the outer carapace may be unravelled in dissected areas on the flanks, and relict reef structures capping the seamounts or guyots may be examined with manned submersibles or ROVs.

4. BACK-ARC MARGINAL EXTENSIONAL BASINS. ALVIN has already been used on a limited basis for examination of the spreading centers of back-arc basins that lie shallower than 4 km, but much more work remains to be accomplished in the coming years and some of these spreading centers lie at depths beyond ALVIN's reach. Differences between MORs, back-arc basins with discrete spreading axes, and back-arc basins with more diffuse spreading is important. The differences in basin geometry, sediments, and the chemistry of the volcanics that exist in these locales can be used to compare with ophiolites exposed on land.

5. TRENCHES. The floors of most trenches lie deeper than 4000 m, so the present capability of ALVIN does not enable U.S. scientists to investigate them. Important problems exist both where the floors of the trenches intersect the landward slope and also higher up on the slope. Small scale offscraping and deformation at the toe of the landward slope should be studied in trenches where there have been recent earthquakes. The deformation may be observable, or it may be buried under slides or slumps resulting from the earthquakes. Evidence for older deformation on strata that crops out on slopes, and possible evidence of the traces of faults which occur above the basal thrust, must be examined visually after prior surveys with Seabeam, Sea MARC, and high resolution seismic profiling.

CONTINENTAL RISE AND DEEP-SEA FANS

Some of the comments made in the following sections on the geology of the continental shelf and upper continental slope apply to the sedimentary processes and depositional patterns of these environments as well. Sedimentary processes and rates of accumulation of sediments have changed drastically since the lowered sea levels of the late Quaternary. When the shoreline lay at the edge of the continental shelf, large volumes of terrigenous sediments were introduced into the ocean directly to the continental slope and to the abyssal plains. Since the late Quaternary and Holocene transgression, these environments have been far removed from sources of terrigenous sediments, which lie landward of the continental shelves. Rates of accumulation of sediments therefore decreased significantly at between 10,000 to 15,000 years BP from low sea level conditions to present high sea level conditions. Sediments are being introduced in significant quantities to these basal slope environments today only where submarine canyons head in the shore zone.

Basal continental slope and abyssal plain deposits are generally featureless, with only local, low-relief (<1-2 m). Use of submersibles is therefore limited to detailed localized study (such as the special problems associated with study of the benthic boundary layer and/or emplacement or servicing of instrument packages) or local-scale biological studies. However there are restricted environments of higher relief such as turbidity current channels on deep-sea fans and abyssal plains. Submersibles can be used effectively for observations and detailed sampling of natural levees, fan valley flanks, terraces, and inner incised channels in more complex fan valleys. Many of these fan valleys are inactive today or are being backfilled by small turbidity currents. The natural levees and adjacent fan and abyssal plain surfaces are receiving only pelagic sediments because Holocene turbidity currents were not large enough to fill the channels and overtop the levees. These processes are important because of the impact of bottom current patterns on slope stability.

BENTHIC BOUNDARY LAYER REGION

The benthic boundary layer region, the interface between the water column and sea floor (including the water overlying the sea floor), is a structurally complex zone of coupling and transition between benthic and pelagic environments and processes. There are often well-developed layers or strong vertical gradients (at the mm to 10's of m scale) of current velocity and shear, potential temperature, and concentrations of various dissolved substances, particulates, and organisms. Species endemic to the benthic boundary layer occur, and there is evidence for enhanced biological activity. This region is a distinct, ubiquitous, and important feature of the oceans worldwide.

A number of significant scientific questions concerning benthic boundary layer processes are presently being investigated or are likely to be explored in the near future, and submersibles have and will continue to play a major role in these studies. Areas of present and future research include:

1. Biogeochemical cycling, especially processes at or near the sediment-water interface. The rates and mechanisms of organic matter transformation are a particular interest of the NSF Global Ocean Flux Study.

2. The energetic coupling between pelagic and benthic communities, including particulate fluxes, metabolic rates, the modification and repackaging of particles by benthic boundary layer organisms, and the role of microbes. These processes, and several others listed below, figure strongly in the NSF GLOBEC research initiative.

3. Sediment-flow interactions, including analyses of particle deposition, resuspension, and transport. The study of nepheloid layers, benthic storms, turbidity flows, sand waves, and the palaeoceanographic record are additional areas of research.

4. Organism-sediment-water column interactions. This includes bioturbation, the production and disappearance of biogenic structures, the biological alteration of sediment characteristics, solute transport through sediments by burrow irrigation, and how these biological processes interact with near-bottom flow fields and sediment transport.

5. Topography-flow interactions. At the mesoscale level, physical and biological effects of flow through submarine canyons and near seamounts are a focus of the ONR Abrupt Topography program. The formation of eddies and wakes, enhanced productivity, and effects on animal distributions are some of the topics of research. At smaller scales, the effects of flow over small topographic features and how these small-scale mixing and eddy processes affect larval settlement and dispersal, animal distributions, and sediment characteristics are being studied.

6. Vent and seep processes. These include fluid discharge and mixing, heat flow, geochemical transformations, microbial ecology of vent communities, the biology of their constituents, and larval dispersal.

7. Horizontal and vertical animal distributions in the benthic boundary layer region. A knowledge of community structure (species, size classes, functional groups), behavior, vertical migrations, metabolism, food webs, and the spatial and temporal variability of these parameters is critical for understanding all biologicly mediated processes in the benthic boundary layer.

8. Biological and mineral resource management. For biological resources, this includes the study of commercially important demersal or vertically migrating fish, the near-bottom planktonic food of these fish, and the operation of fishing gear. For mineral resources, the monitoring of exploration and recovery operations such as ocean drilling and mining is essential to properly assess the ecological impact that these operations may have on benthic communities.

9. Pollution analyses such as the monitoring of dump sites, potential nuclear waste disposal sites, and urban and agricultural runoff and wastes that sink near the bottom.

SEDIMENTARY BIOGEOCHEMISTRY/GEOCHEMISTRY

1. Documentation is required of chemical property distributions associated with specific structures or features of the seafloor on a variety of scales (100 mm - 100 m). Sharply-scaled and complex geometrical distributions of reactions, reactants, and reaction products typically characterize the most important chemically active sites at the seafloor. These sites, within larger, major environmental regions, include: the sediment-water interface, biogenic sedimentary structures, hydrothermal vents, hydrothermal mounds, and cold seeps (sulfide or brine). Precisely-oriented in situ sampling and placement of instrumentation is required. Interactive sampling and observation permits minimal, rigidly-programmed sampling protocols. The lability of certain features, such as pore water solute distributions and easily oxidized minerals, requires knowledge of sample handling/history throughout collection procedures; thus these operations cannot be conducted indirectly by means other than submersibles.

2. Direct measurement of reaction rates in bottom deposits. The rates and kinetic relations of many major biogeochemical reactions such as aerobic respiration, nitrate reduction, manganese reduction, and sulfate reduction, vary substantially in different regions of the sea floor and with depth in the sediments at any given site. Rates of authigenic mineral formation or dissolution (for example, $CaCO3$ precipitation - dissolution) scale in similar ways. There are no reported in situ reaction rate distributions. All present estimates are made indirectly by transport-reaction modeling of property distributions and net flux measurements of a few select solutes across the sediment-water interface. Accurately oriented in situ placement of measurement instrumentation and experimental manipulations are required to elucidate rates and their determining factors.

3. Measurement of net fluxes of biogeochemically important solutes at the sediment-water interface. Remotely-deployed landers provide one means of estimating net fluxes by monitoring rates of change of solute concentrations in isolated incubation chambers. A degree of conditional sampling associated with specific physical or biological structures (mounds, burrows, tubes) is necessary to understand processes controlling net fluxes and their variability. Rates and styles of biogenic irrigation and particle reworking must be evaluated. Oriented sampling and interactive placement of instrumentation is required.

4. Investigations of the nature of biotic/chemical interactions connected with dynamic oxic-anoxic interfaces such as cold seeps (sulfide or brine), hydrothermal vents (sulfidic or hydrocarbon), or biogenic structures. Chemolithotropic associations and their roles in elemental cycling near specific zones of oxygen-reduced species contact, remain an area of major future research. Oriented sampling, manipulative experiments, and interactive placement of instrumentation is required.

BENTHIC BIOLOGY

1. Documentation is needed of the scales of variability in macro-, meio-, and microfaunal distributions and abundances on and in the seafloor. Specific aggregations, orientations, and emigration-immigration patterns of benthos with respect to biogenic and physical sedimentary structures, cold seeps (sulfide and brine), and hydrothermal vents are minimally characterized. Conditional, spatial, and time series sampling is required. Direct three-dimensional observations of relationships are necessary.

2. Direct measurements are needed of microbial and general faunal metabolic activity. Rates of carbon and nutrient cycling on the deep-seafloor remain poorly characterized. In situ measurement of activity distributions and temporal patterns requires accurate and oriented placement of instrumentation and experimental manipulation.

3. We must investigate the response/adaptations of benthic communities, populations, and individuals to varied physical, chemical, and biological disturbances. These adaptations include reproduction, recruitment, and growth (life history patterns) as well as behavior. Examples of classes of periodic or stochastic disturbances include: bioturbation, influx of organic material (food), waxing-waning-migration of cold seeps or hydrothermal vents, physical disturbance by currents and sediment transport (erosion - deposition), and anthropogenic disturbances such as mining or dumping activity. A quantitative description of disturbance and the relative role of disturbance in controlling distributions and abundances in different regions of the seafloor requires substantial further study. These studies need conditional sampling, experimental manipulations, and oriented instrument emplacement.

4. We must conduct in situ experimental investigations of a variety of characteristics related to behavior and adaptation including physiological properties, animal-flow interactions, and animal-sediment interactions (morphology, feeding type, life habit). These would include feeding behavior and activity response to flow variation, impact of biogenic structures on animal distributions and activities, and species-specific patterns of particle reworking/burrow irrigation. Such studies bear directly on remineralization rates and nutrient recycling in the benthic boundary region. Manipulative experiments and instrument emplacement (for example, flumes) are required.

5. Direct investigations are needed of the character of biotic interactions in seep and/or vent areas. Also the role of the biota in the generation of structural features.

SUBMERSIBLE CAPABILITIES REQUIRED FOR SCIENCE PROBLEMS ON THE DEEP SEA FLOOR

A. General Capabilities

1. Submersibles and their support ships must have accurate navigation systems that allow them to carry out field programs over large geologic structures without always having to be tied to cumbersome and time- and labor-intensive seafloor transponder arrays. Current state-of-the-art would be an integrated system that includes a short-baseline system involving directional transducer/receiver arrays on the surface ship, single transponder beacons on the seafloor and ship navigation on a 24-hr/day basis using GPS positioning.

2. Submersibles should be able to go faster and cover larger distances over the seafloor in a "survey" mode. This implies the availability of high-resolution (1 m or less) downward looking echo sounders, and high-frequency (c.a. 100 kHz) side-looking sonars, as well as photo-electronic imaging systems. This capability may be met through a combination of manned and unmanned systems. Towed systems

in the tradition of DEEP TOW, offer a strong alternative for large-scale survey because of their payload potential and their unmatched endurance. With the addition of fiber optic cables, both towed systems such as ARGO, and powered systems like RUM III will have a significant increase in their ability to return data, if they are fitted with appropriate sensors.

3. The need for drill-core sampling of volcanic, igneous, or indurated sedimentary rock outcrops will be important in future submersible investigations in diverse geologic settings. This type of technological advance includes both manipulator mounted drill bits as well as small, portable coring apparatus that can be deployed by the submersible and left to conduct its sampling work while the submersible tends to other mapping chores.

4. Forward- and side-looking sonars (CTFM = continuous transmission frequency modulation) that are suited to detecting hydrothermal vent sites or areas of unusual thermal or bottom water turbidity would be a great boon to the overall effort of mapping hydrothermal vent areas and correlating the various chemical, biological and geological parameters of seafloor hydrothermal systems.

B. Capabilities Required to Support Ocean Floor Laboratories

An important aspect of MOR studies that will take place in the decades to come is the installation of ocean floor laboratories and periodic revisitation to ridge crests where hydrothermal venting and biological colonization occur. The oceanographic community has arrived at a consensus regarding the need for long-term observations of physical, chemical, geological and biological processes on MOR crests.

1. Biological, Chemical and Geological Sensor Arrays - will be permanently installed in ocean floor laboratory complexes and will allow for the measurement and recording of complex and interrelated magmatic, volcanic, deformational, hydrothermal and biological processes on time scales from <1 second to >1 year. Manned submersibles and ROV's will play pivotal roles in the deployment, monitoring and servicing of seafloor laboratories. These functions will include both pre-deployment site-surveys to collect engineering-scale data for fabrication of the instrument modules, as well as actual deployment and on-site assembly of the systems. Manned submersibles and ROV's will also be used to monitor the function of laboratory sensor arrays, recover data packages and install new power supplies.

2. Borehole Instrumentation and Submersible Systems Support - will clearly represent an important facet in the ocean floor laboratories concept. The coupling of the biological and chemical investigations to crustal drilling reflects the multidisciplinary approach required to solve key oceanographic problems. The instrumentation of these boreholes with various physical and chemical sensors and the maintenance of the seabed laboratory by submersible systems (both manned and unmanned) will place greater scheduling and technological demands on submersible facilities.

C. Capabilities Required for Study of Benthic Boundary Layer Problems

The use of submersibles has been and will continue to be vital to the study of benthic boundary layer processes because of the need for precise sampling and manipulation, the need to precisely control altitude, and the importance of direct observations of this complex habitat. In addition to the capabilities necessary for benthic or water column work, there are some special requirements for submersible work in the benthic boundary layer. These include:

1. The submersible must have precision altitude control. It should be able to hover and move horizontally at specific altitudes (resolution of 1 m) and to make repeated and rapid fine adjustments in buoyancy to change altitude or to maintain a constant altitude even in regions of rough topography. A maximum speed of several knots would be very useful, not only to allow wide-ranging transects, but also to follow large, fast-moving animals.

2. The submersible should be able to hover, move, and conduct sampling operations in the water column or while resting on the bottom, with minimal sediment or flow field disturbance. The use of downward directed thrusters, for example, is inappropriate for much benthic boundary layer work. Adjustable buoyancy systems and variable ballast systems for trim control can resolve these problems.

3. Observers must be able to see, photograph, and precisely manipulate objects (ranging in size from mm to m) both on the bottom and in the water column on the same dive. Photographic and lighting systems adjustable for both benthic and pelagic work on the same dive, viewports placed a short distance from the bottom, a wide field of view, and viewport engineering designed to minimize water entrainment are essential.

4. The incorporation of sensors, data loggers, and possibly specialized guidance systems to measure and track the physical gradients in the benthic boundary layer is needed. This includes at least a CTD and transmissometer, and possibly (after further development) high frequency acoustics (for measurements of currents, particles, or biomass) and terrain-following or isoline-following guidance systems. A long extendable manipulator arm or probe with sensors would be useful for reaching precise features or small areas inaccessible to the entire submersible, with minimal sediment or flow disturbance. Devices to sample the "fluff" layer and upper sediments at precise depths (mm to cm) with minimal disturbance should be refined and made available.

SHELF AND UPPER CONTINENTAL SLOPE

Significant use has already been made of shallow-water (<1000 m) submersibles for biological, geological and other research on the continental shelf and upper slope and in large lakes, supported primarily by institutional, Department of Commerce (NOAA) and National Science Foundation funds. The work represents a blend of mission-oriented and basic research interests being addressed by scientists in academic, government, and private institutions. Most of the submersibles used, with working depth ranges of 300 to 1000 m, have been leased from commercial operators, and the operations have generally been successful. Science needs, reviewed below, are important enough that accessibility to these shallow diving submersibles and ROV's must be improved. At the present time, for example, NSF-supported scientists invariably encounter major difficulties in obtaining funding for the use of these kinds of facilities. Another problem is geographical imbalance, wherein west coast researchers have virtually no access to facilities support programs.

GEOLOGICAL PROBLEMS

An illustration of the importance of studying sediment distribution and sedimentary processes on continental margins is a new national initiative for "Continental Margin Integrated Sedimentation Studies" (CMISST).

The sediment distribution on continental margins is out of equilibrium with present environmental conditions because of the relatively rapid and recent changes of sea level during the late Quaternary. During the last glacial maximum, about 18,000 years BP, the shoreline lay approximately at the edge of the continental shelf. The transgression accompanying the rise of sea level was so rapid that deposition of only shore zone sediments occurred mainly across continental shelves. As river mouths retreated up their estuaries, many shorelines stabilized approximately 5000 years BP, and progradation has occurred where the influx of sediments has been sufficient to overwhelm the currents and waves transporting sediments away from river mouths. Most of the surface of broad continental shelves and most shelf edges, however, are still covered with relict shallow-water sediments. Continental slopes are also out of equilibrium, and today only relatively minor amounts of sediment bypass the shelves to be deposited on the slope. Submarine canyons, which during lowered sea level fed the continental rises and deep-sea fans, continue to do so today only where the shelves are narrow and the canyon heads are near the present shore zone. As a result, most base-of-slope sedimentary environments, i.e. continental rises and deep-sea fans, are receiving lower rates of accumulation of sediment today than they did during lowered sea level.

Studies of sediment distribution patterns and the dynamics of sediment transportation and deposition have suffered because estimates of present processes of distribution and transportation are made by an indirect approach rather than by direct measurement or observation. CMISST initiatives will give new emphasis to better direct observations and study of these dynamics. Some of these studies could be conducted much more effectively and efficiently through the use of submersibles capable of working on the continental shelf and upper continental slope.

Much of the surface of the continental shelf is rather featureless at large scale, with low relief that can be surveyed and sampled adequately from surface vessels. Exceptions are small-scale resolution and the emplacement and servicing of bottom instrumentation, doing detailed studies of the biology or sediment transport processes in small areas, or making observations in areas of higher relief. Therefore, among the direct applications we foresee in the use of submersibles on the shelf and upper slope are:

1. Placing and servicing of instrumentation, experimental apparatus, sediment traps, etc. for longer-term periods of observation.

2. Observation of the relict shore zone sedimentary deposits at the shelf edge, and especially where cemented to beach rock.

3. Mapping and sampling of bedrock outcrops.

4. Study and sampling of shallow submarine canyons, or the heads of deeper canyons, including morphology, agents of erosion, bedrock and late Quaternary stratigraphy of the walls of the canyon, and transportation processes of sediments down the axis of the canyon.

5. Studies of the morphology and the relation between biology and geology of atolls, reef flanks, or patch reefs on the surface of the shelf.

6. Study of sediment transport processes and relationship to current motion at and over the edge of the continental shelf.

7. Study of the lithology, stratigraphy, and morphology of slump scars and deposits on the upper continental slope.

8. Observation and sampling of dateable material from former stands of the shoreline during Pleistocene-lowered sea level on the shelf, at the shelf edge, in wavecut terraces on the upper continental slope, and at the heads and walls of submarine canyons.

BIOLOGICAL AND FISHERIES PROBLEMS

1. Life history and ecological studies of commercial and recreational species are necessary, to better understand population dynamics and year class fluctuations including predator-prey relationships, spawning-ground requirements, nursery ground characteristics and impacts from intensive fishing. These are all important categories of information needed to wisely manage living marine and fresh water resources. Conventional, surface-oriented techniques have "reached their limit" in terms of producing much of this additional life history and faunal response information.

2. A variety of man-induced physical and chemical stresses have been added to those naturally occurring in our aquatic environments. Living resources and their ocean and lake floor habitats are now subjected to intense and repeated stress from mobile (trawls, dredges) and fixed (traps, gillnets) fishing gear. Multiple use (fishing, hydrocarbon exploration, ocean dumping-sewage sludge, dredge spoil, industrial wastes, etc.) of our coastal waters and large lakes is now commonplace and will probably continue through the foreseeable future. The reaction of these shallow water habitats and their associated biota must be understood to prioritize this multiple use and minimize damage. To accomplish this goal requires an increased understanding of the biogeochemical processes operating within the benthic boundary layer (see item 3 below). For example, bottom trawling and dredging can greatly disfigure ocean floor habitats. Is this a serious impact? Or, "ghost" gill nets and traps may continue to fish for years on the ocean bottom, entrapping a wide variety of fauna. Does ghost fishing gear represent a serious uncontrolled loss to our fishery resources? Many other important examples are pertinent to this research area.

3. The biogeochemical processes occurring within the nepheloid and fluff layers and surficial sediments of the shelf/slope benthic boundary layer, appear to play a major role in determining biological productivity of aquatic ecosystems. Bacteria and other micro-organisms transform nutrients and pollutants in the fluff and nepheloid layers, bottom-oriented fishes, crustaceans and zooplankters redistribute these elements through bioerosion, and the feeding and fecal pellet production cycle further extends this transformation and redistribution. The fluff and nepheloid layers are hypothesized "cleansing zones." This research theme is currently receiving considerable interest and support within the shallow water science community; this interest and support is expected to continue well beyond the 1990's.

4. Animal/plant substrate relations and the role of bioerosion is the subject of considerable research interest and support. Shallow ocean and lake floor living resources are, to a large degree, bottom oriented. Their productivity is primarily linked, directly or indirectly, to substrate characteristics. Environmental parameters governing productivity of hard and soft substrates will continue to receive considerable attention in the near future from biological, physical and chemical scientists.

5. Sedimentary processes governing the redistribution of sediments and the formation and maintenance of sedimentary features, remains a common research theme within the shallow water science community. Ground-truthing seismological and side-scan sonar imaging is a major aspect of this research theme.

6. Calibration, ground-truthing and the study of the behavior of sampling and fishing gear continues to be an important function of in situ methodology of the shallow-water, bottom-oriented scientist in both the marine and fresh water environments. Sampling

gear such as punch cores, box cores, fluff layer samplers, electro-suction samplers, collimated light/video samplers of nepheloid particles and zooplankters, laser gun video documentation techniques for assessing bottom and epibenthic fish populations on level and rough bottom terrain, time lapse video and sonar triggered cameras, recolonization substrates (natural and artificial) and fishing gear such as traps, gillnets, trawls, dredges and long lines are the primary focus of this attention.

COUPLED PHYSICAL AND BIOLOGICAL PROCESSES

1. Identification and study of the small-scale biological and physical processes affecting larval recruitment in both planktonic and benthic stages.

2. Determination of the effects of wave surge and other types of turbulence in subtidal habitats (e.g., sedimentation, resuspension, larval settlement, nutrient fluxes).

3. Examination of the effects of latitude and depth gradients on the distribution and abundance patterns of subtidal organisms; the correlations of these patterns with physical parameters, and experimental tests of these correlations.

4. In situ studies of the biomechanical properties of subtidal organisms.

5. Investigations of the significance of long-term cyclic patterns as well as unpredictable events in determining the structure and functions of subtidal communities (how do these disturbances influence competition, predation, resource availability, and recruitment?).

6. Investigations of the interactions between the benthos and the overlying subtidal waters (e.g., nutrient fluxes, emergent plankton, transport of materials, benthic boundary layer effects).

SUBMERSIBLE CAPABILITIES REQUIRED FOR SHELF AND UPPER CONTINENTAL SLOPE RESEARCH

1. The payload of the vehicle must be as large as possible, within practical limits, to address replicated sampling, sensing, manipulation and photo-documentation tasks on a dive-by-dive basis.

2. The vehicle must be highly maneuverable and able to hover and maintain position in currents up to 1.5 knots. Minimal disturbance to the bottom is necessary.

3. Capacity to carry two scientists is often useful, but not always necessary. Ample room for the scientist(s) and internal equipment is very important; human comfort is a key factor in scientific productivity on long-duration dives.

4. Viewing characteristics in low visibility environments are critical to scientific productivity, especially in the direction of the ocean or lake bottom. Eye to subject distance should be no more than 1 meter; externally-mounted video cameras are not a suitable substitute for good direct viewing capabilities.

5. The cost of a total dive system should not exceed $7,000-8,000/day and it should be capable of taking 6-10 scientists to sea per cruise.

6. The support vessel must be capable of performing standard surface oceanographic tasks such as XBT casts, CTD casts, operating a small- to medium-sized gravity punch core or

box core and setting/retrieving a variety of sensing, and monitoring equipment to complement the in situ operations.

7. The submersible must have at least one 6- or 7-function electric or hydraulic robotic arm capable of smooth, precise manipulations. This is a very important requirement. In addition there must be appropriate sample receptacles for storing, and retaining undisturbed punch core and box core samples, delicate fauna, etc. Site specific revisitation, and manipulative experiments are becoming commonplace in shallow water research; this trend is expected to continue.

8. High-resolution, low-light-capable video documentation and 35 mm still photography continue to be important requirements for submersibles.

9. A real-time CTD logging system with digital display and current meter (direction, speed) capabilities should be standard equipment on research submersibles.

10. Mounting locations, through-hull penetrators and vehicle payload capabilities should permit the use of varying combinations of sampling and sensing equipment listed under Biological and Fisheries Problems above. Scientific productivity is closely tied to such capabilities where the scientist can directly observe and video document a specific sampling procedure.

11. Precise tracking and logging of the submersible track or working location is necessary; the scientists should have a hard copy plot of the working dive.

12. Active and passive sonar capabilities are an important capability for submersibles to orient to specific objects and features on the bottom and for pinger orientation.

WATER COLUMN

In most respects we have reached the limits of what can be learned from conventional methodology alone. In order to make significant new progress in our understanding of midwater ecology and chemistry, we need new kinds of information; not more of the same. The midwater habitat is the largest living space on earth and yet our knowledge of it is so profoundly poor, that in most cases we are just beginning to comprehend its complexity.

MIDWATER BIOLOGY

1. We need accurate assessments of the identities and relative abundances of the principal constituents of the midwater fauna. It is clear in even the limited data presently available from mesopelagic submersible use (and by analogy from blue-water plankton research) that nets and acoustics have greatly underestimated the abundance of gelatinous zooplankton and of micronekton. As a result, our general concepts of midwater community structure based on conventional sampling, are considerably in error.

2. We need to resolve animal distribution patterns on a 3-dimensional scale of 1 m to 1 km. Net tows integrate distribution data over hundreds of meters at best, and acoustic systems are "deaf" to a majority of the animals. As yet we have no fine-scale picture of how a mesopelagic community is even put together, much less how it works. The oceanic water column is a more truly three-dimensional habitat than any other, and this characteristic means that direct observations are far more efficient than indirect methods for assessing patterns of distribution and abundance.

3. We need to observe the behavior patterns of midwater animals in their natural habitat. Indirect sampling tells us almost nothing about animal behavior. In situ behavioral observations provide information on the dynamic aspects of ecology and are often the key to understanding patterns of community structure. They are also essential for the application of physiological rate data to energy budgets. As an example, bioluminescence is a very widespread characteristic of mesopelagic animals (roughly 90% of all species), yet our knowledge of how it is used is entirely speculative because there have been no direct observational studies.

4. We need to conduct manipulative experimental work in situ: including live captures, in situ incubations, and time-series studies. Direct access to the habitat is fundamental to nearly all branches of terrestrial ecology, but in marine habitats these capabilities are relatively new. In situ studies of the deep-sea floor by ALVIN and of epipelagic communities by blue-water scuba divers, have generated major changes in our understanding of biological processes at the bottom and at the top of the oceanic water column. The next logical step is to extend this proven methodology into midwater.

MIDWATER CHEMISTRY AND PHYSICS

1. Vertical flux processes and the transport of particulate organic matter.

2. The generation, ecology and fate of marine snow.

3. Ground-truthing of sediment traps.

4. Direct observation and measurements of sinking rates of a variety of particle types.

5. Isolated collection of individual particles for discrete chemical analysis.

6. Study of the chemical micro-environments around suspended and/or sinking particles and aggregates.

7. Resolution of fine-scale physical processes such as mixing vortices and interface structure and dynamics. Visualizing these processes may require advanced dye-injection techniques. Alternatively, coupled biological studies may also indicate the nature of physico-chemical phenomena, because of the tendency of the midwater biota to aggregate at interfaces and disperse along gradients.

8. Real-time integration of instruments and vehicle navigation allow for the three-dimensional mapping of physico-chemical features in the water column. Modern analytical sensors coupled to "terrain following" navigation software that can follow isopleths or gradients of a wide range of significant parameters will be necessary.

9. An important aspect of the in situ capabilities offered by submersibles to water column physics and chemistry is their versatility of perspective. Investigations can be readily conducted from either the lagrangian or eularian points of view, that is, flowing with or holding position within currents.

SUBMERSIBLE CAPABILITIES REQUIRED FOR MIDWATER RESEARCH

1. A depth limitation system that will automatically prevent a manned midwater submersible from exceeding its operational depth. At present, most such subs are not allowed to work in water depths greater than their operational limits because of insurance constraints. This has limited their use to coastal waters. Development of a reliable depth-limiter will greatly enhance the utility of midwater subs by expanding their

operating area from less than 10% of the world ocean to more than 90%. The design and testing of such a system do not present a major engineering challenge.

2. Improved battery technology to reduce size and weight while increasing power and endurance. Dive duration at moderate power utilization should encompass at least 6-8 hours.
3. Quiet, simplified electric motors to replace the noisy hydraulic thrusters now frequently in use.
4. Improved imaging systems (e.g., range-gated cameras, low-light video systems, spectral analyzers, laser illumination and ranging systems, etc.)
5. Miniaturization of sonar systems for deployment on smaller, lighter vehicles.
6. Development of fiber optic tethers and/or data communication linkages to the surface.
7. Non-traditional sensory capabilities (e.g., chemosensory or electrosensitivity) to allow for "terrain following" control systems that are cued by non-navigational input devices.
8. Improved buoyancy/ballast control technology.
9. Improved tether cable management systems.
10. Data logging and integration systems.
11. Simulators for personnel training.
12. Improved technology for combining manned and unmanned systems (e.g. ROV's deployed from manned vehicles and/or remote control systems for manned subs).
13. Specific adaptations for working in polar regions and under-ice habitats.

ESTIMATED LEVELS OF UTILIZATION

The following projections are based on several sources of information, assessed between 1986 and 1989: (1) interviews with researchers who presently use submersibles in their work, with those who wish to begin using them, and with graduate students; (2) discussions with commercial and academic operators of submersible systems; (3) discussions with research and facilities program managers at NSF, ONR and NOAA; (4) research and development engineers; (5) manufacturers of submersible vehicles; and (6) workshops on submersible utilization.

The needs of the ocean research community for both manned and unmanned submersible systems will continue to expand through the next decade. Examples of "new" users include NSF's Division of Polar Programs, the National Park Service, the Environmental Protection Agency, and the Department of Energy. At the present time, demand far exceeds availability. This condition will continue so long as there is no mechanism for making this technology readily available to the majority of the research community. Because these needs are not being met, the logical development of scientific progress in many critical areas of marine research is being stifled. Submersible systems should no longer be regarded as exotic and expensive tools by the three federal agencies which fund the bulk of basic ocean research, but rather as critical facilities needed to further oceanographic research on a regular basis.

Given a suitable means for providing access to submersibles -- that is, a system that handles requests for submersible facilities support as matter-of-factly as ship-time requests -- we believe that by mid-decade the annual demand for submersibles to facilitate funded research projects will be at about the following levels:

- continued full utilization of ALVIN,
- 100+ days of time aboard manned vehicles capable of reaching 6 km, ramping up to a full year of use by the end of the decade (e.g. SEA CLIFF, NAUTILE, MIR),
- 850 days of time aboard single- and multi-seat manned submersibles operating to depths of 1 km or more (e.g. DEEP ROVER, Johnson-SEA LINK),
- 600 days of time using deep-diving (2-5 km), general purpose, unmanned ROV's from ships of opportunity as well as from dedicated support vessels (e.g. HYSUB, JASON, ARGO), and
- 1,000 - 1,500 operational days for small, shallow-working (500 m), low-cost ROV's (e.g. PHANTOM, MINI-ROVER).

Submersible systems will be needed by all of the federal ocean research agencies, for both their core research programs as well as for all of their projected global-scale programs. Biology and geology will be the disciplines most requiring these facilities, at least for the first half of the decade. Chemical oceanography needs will be intermediate and needs for physical oceanography will probably ramp up the slowest. This demand is very real and very strong. These needs will greatly exceed our present federal facilities and our organizational capabilities to deal with them. Given adequate access to the needed systems, by the end of the decade, submersible technology will be the principal source of primary oceanographic data.

These levels of utilization will not require large, short-term capital investments in facilities. Most of the submersible systems necessary to meet these needs are already at hand. ALVIN and SEA CLIFF are extant federal vehicles. And with the exception of two manned submersibles in the DEEP ROVER/SEA LINK category, all of the remaining projected dive days can be met by leasing existing hardware from commercial, academic, and foreign-flag operators.

ASSESSMENT OF SUBMERSIBLE CAPABILITIES AND TECHNOLOGICAL NEEDS

REVIEW OF VEHICLE TYPES

Submersible science has been supported by a number of types of vehicle systems. These include manned submersibles and a variety of unmanned or remotely operated systems that have different but often complementary capabilities. The evolution of these systems reflects an interplay between science needs, practical technological capabilities, budgetary considerations, and support vessel requirements and availability.

MANNED SUBMERSIBLES have played a dominant role in submersible science, primarily due to their versatility and availability. Placing the scientist physically at the place to be studied was the only option before remotely operated vehicles existed. The strengths of manned submersibles include direct viewing by the scientists, movement unconstrained by a tether cage, and the ability to accommodate a variety of tools and instruments. Manned systems are best suited to circumstances requiring precision, maneuverability and mobility, and for multiple task missions. Manned systems allow the simultaneous integration of observational data from all three spatial dimensions. Reliability and safety records for the mainstay U.S. scientific manned submersible have been excellent. Whether any type of "remote presence" will ever completely replace such systems is a hotly debated issue. In the context of the present report, the issue is irrelevant because we need both types now.

1. Tethered vehicles. Tethered, manned submersibles comprise two basic types – diving bells and atmospheric diving suits (ADS) – both types were developed chiefly for the offshore oil industry. Bells, surface-powered or with onboard batteries, have been used primarily for seafloor structures observation and manipulative mechanical functions. ADS systems have been used successfully to support scientific research. They are typically small, one-person vehicles that provide excellent visibility and manipulative capabilities either in midwater or on the seafloor. ADS systems (e.g. WASP, MANTIS) are small and can be readily deployed from ships of opportunity.

2. Untethered vehicles, moderate depth range (1000-1500 m). These manned submersibles are self-powered, free-swimming platforms with space for from one to four persons. Some have acrylic personnel spheres which provide excellent panoramic visibility. Older systems are generally restricted to working on the bottom and have limited maneuverability. More modern systems function well in midwater as well as on the bottom (e.g. DEEP ROVER, Johnson-SEA-LINK). The larger systems require a dedicated support vessel while the smaller ones can be operated from many UNOLS ships.

3. Deep-diving, untethered vehicles. These manned vehicles carry from two to three personnel within metal pressure spheres borne by battery powered thrusters. Typically these submersibles (e.g. ALVIN, PISCES V) are designed to work on the bottom and their layout of tools and manipulators as well as the configuration of their observation ports are designed to facilitate this mode. These vehicles are large and relatively costly to operate and they require dedicated support vessels.

UNMANNED OR REMOTELY OPERATED VEHICLES have appeared in the last 20 years, with developments pushed by both military and commercial offshore needs. A variety of types have evolved, some quite specialized. When compared to a manned submersible, they may be more limited in capabilities but are often more economical in the specific job they were designed to perform. Unmanned systems are best suited to long-term observations in stationary circumstances, or for covering large areas of seafloor and for single task missions. They are clearly superior for hazardous circumstances, for missions requiring long endurance, and for locations difficult to access.

1. Towed survey vehicles (e.g. DEEP TOW, ARGO). These vehicles rely primarily on ship movement and forces applied by a tow cable to control mobility. They are used chiefly for seafloor or midwater survey tasks over large areas and are characterized by great endurance. Typical missions include side-looking sonar, video, or still-photographic surveys. For all but some of the simplest film photography vehicles, the tow cable is usually a .680", coaxial armored cable capable of delivering power and carrying telemetered signals.

2. Self-propelled tethered vehicles (e.g. HYSUB, JASON). These vehicles move through active propulsion systems with power and telemetry delivered through a tether cable. Real-time video is used by the pilot on the surface to guide the vehicle movement, often complemented by various types of sonars. For present implementations, the viewing for both piloting and scientific observations is inferior in most respects to direct viewing from a manned submersible. The larger vehicles of this type have some sampling capabilities similar to manned submersibles, but lack the precision of three-dimensional visibility or broad depth-of-field for sampler deployment. Their strong suits are endurance, simultaneous high-bandwidth sensor deployment, and real-time data transmission to storage and processing computers topside.

3. Bottom supported vehicles (e.g. RUM III). Such a vehicle is lowered on a cable and can be placed on the seafloor after which it can move short distances with tracks. Substantial negative buoyancy provides a very stable working platform and allows the vehicle to perform sampling tasks requiring forces higher than those for a manned submersible or a neutrally buoyant ROV. Payload potential is very high.

4. Untethered remotely operated vehicles (e.g. ARCS, EPAULARD). Several examples exist of vehicles that are untethered and controlled through acoustic links. They have the advantage of improved speed and mobility due to the lack of a tether, but also have limited endurance, they provide only low bandwidth feedback to the operators and scientists, and require moderate amounts of onboard decision making. The advantages of these vehicles compared to towed system can be projected directly but have not yet been demonstrated.

5. Autonomous vehicles (e.g. EAVE EAST). The remaining type of vehicle functions with no human intervention for long periods, perhaps weeks or months and can be considered autonomous (AUV). While existing stationary, moored, or drifting instruments function "intelligently?" for long periods, they lack the controlled movement of a submersible vehicle. Such vehicles have a number of attractive applications where tethers or acoustic telemetry are impossible or where operation without the presence of a surface support ship is needed. Potential science applications include under-ice studies, long-range water column studies, and long-term monitoring or survey. These systems are a logical outgrowth of untethered vehicles controlled through acoustic links.

NEEDED TECHNOLOGIES

A variety of technological developments could improve the capabilities of submersible science activities directly. Some of these apply principally to a specific class of vehicles, but most apply to nearly any type of vehicle system.

1. TELEMETRY SYSTEMS

Two types of telemetry offer very substantial gains for submersible science: acoustics and fiber optics. Prototypes of these systems directly applicable to science use have either been tested or are in development. There remain several steps however, for operational reality.

Acoustic links have been demonstrated over both vertical, deep water paths as well as the more difficult shallow horizontal configuration. Such systems are capable of modest data rates (several thousand baud). They would greatly enhance the utility of manned submersibles, by permitting near real-time observations by additional scientists on the surface. Such technology is crucial to the development of untethered vehicles supervised from the surface.

The potential of fiber optics to provide improved scientific access to the ocean, particularly at great depth, cannot be overemphasized. For example, a 6000 meter length of the UNOLS standard 0.68" conducting cable can directly transmit one moderate resolution monochrome video image at a reasonable signal-to-noise level. The equivalent cable with a fiber optic core could transit multiple color channels of the emerging high definition television standard simultaneously with hundreds of megabits/second of digitized data such as sonar or electronic still images. The resulting high quality sensory feedback and responsive control of vehicle and manipulator movements can greatly improve the scientific utility of ROV's.

Fiber optic telemetry is commonplace in the telecommunications and computer industries today, but its use in the ocean requires a number of additional elements that are not yet fully operational. Components such as cables, high pressure optical penetrators, slip rings, cable terminations, optical connectors and heave compensation systems are just emerging as commercially available items. Fiber optic cables also place greater demands on handling systems, an area where existing UNOLS capabilities are uneven. Engineering efforts required to bring these systems on line have been supported piecemeal. However, in applications where fiber optics have been employed (e.g. MBARI) the payoff in clean data transmission has been excellent.

2. IMAGING SYSTEMS

All types of submersible vehicles could be improved by better imaging systems. With a few exceptions, the imaging capabilities of all manned submersibles and nearly all ROV's lag far behind state-of-the-art prime activity.

In the optical domain, many improvements are directly obtainable. Broadcast quality cameras and recorders could be standard features for all scientific submersibles (as they are for a few), both manned and unmanned. Fiber optic telemetry will enable ROV's to transmit the high quality images to the surface, and the new generation of recorders can fit into any and all manned submersibles. Such video systems could be augmented by electronic still camera systems that would replace film for many applications in the near future. Such cameras have exceptional dynamic range (14 bits currently available), good resolution (1000 x 1000 pixels will be available soon), and good low-light capabilities (although not as good as the best intensified video cameras). Developments in high definition should be incorporated into ROV's and manned submersibles as soon as possible. Range-gated laser imaging systems have the potential to extend visual ranges even farther and would enhance any type of submersible. Low-light optical systems are also improving rapidly but few have found their way to use on research submersibles.

Directly coupled to the quality of imaging systems are their light sources. New lighting elements involving novel elements (e.g., sodium scandium) show great promise but lack the low cost and reliability of conventional systems. Laser light sources and specific wavelengths needed for SIT and ISIT sensitivity must also be developed.

3. IMPROVED SENSORS

Currently the suite of sensors available on nearly all submersibles used for science are merely standard oceanographic instrumentation, converted from over-the-side use on conducting cable, to in situ use aboard the vehicle. There is great need for improvement here. The most promising areas currently are both in situ chemical techniques, flow-injection and fiber-optics.

4. SAMPLING TECHNOLOGIES

Sampling is accomplished with dedicated tools as well as with general purpose manipulators. Substantial increases in sampling capabilities are well within engineering state-of-the-art, particularly in the areas of high precision, general purpose manipulators. Dedicated sampling tools such as cores and drills need to be improved.

Despite the evolution of good dedicated sampling tools, general purpose manipulators will always play an important role in submersible science. Commercial underwater manipulators have emphasized strength and simplicity over versatility and precise control of interaction forces. This precludes some dexterity such as that required for sampling delicate objects or for servicing instruments. Several commercial companies are actively pursuing force-reflecting, master-slave manipulator systems that begin to address these problems, but directly coupling end-effector interaction forces back to a human operator is only one method for improved dexterity.

Research and development could advance the state-of-the-art in underwater manipulation in several ways. First, basic underwater manipulator actuation systems should be made more compatible with force control systems. Second, design of end effectors should be improved to make them able to assume a variety of grasping modes with carefully controllable forces. Third, reliable underwater proximity, force, and tactile sensors should be evolved, most likely from existing in-air versions. Finally, improved control systems and man-machine interfaces must be implemented to tie these elements together and make them easy to use.

5. TECHNOLOGIES FOR PRECISE, REPEATABLE SURVEYS

Submersibles of all types should evolve into tools for observing change on several time and spatial scales. To observe change, a vehicle must acquire sensor data while executing accurately navigated and controlled movements. Such capabilities require a variety of technologies that are only now emerging.

Of primary importance are the sensor systems that can make sufficient quantitative observations so that change can later be determined. Existing optical and acoustic imaging systems must be improved so that they yield more quantitative data and are repeatable over weeks, months, or even years. Most existing sidescan sonars are close to the needed level of capability, and the recent appearance of imaging sonars is also very promising.

Another indispensable element is good navigation. While a variety of acoustic systems have been in use for many years, they are not necessarily sufficient as the basis for high performance vehicle control. Short range, high resolution navigation has not received much attention but is clearly a critical need for a variety of survey problems.

Repeatable measurements can be greatly facilitated if the vehicle can return to the same point or fly the same track under automatic control. To achieve good performance, navigation sensors, vehicle dynamics, and control system structure must be carefully matched, regardless of whether the vehicle is manned, remotely operated, or autonomous. Such capabilities are now moving into the advanced development states.

6. DATA MANAGEMENT, VISUALIZATION, AND FUSION

The new generation of submersibles will collect greatly increased amounts of data from vastly different sources. While storage of this data can be accomplished directly, providing convenient access and means for manipulation of the data are serious problems. Integrated management of different types of data such as video, still images, navigation, sonar, and water column measurements has only recently been achieved in limited fashion. More effort and further development of submersible database management is needed. The data must be merged or fused to produce a scientific product without the use of scissors, paste, or colored pencils. Ideally, a scientist should be able to view the data using interactive computer graphics throughout each transformation from raw data to finished scientific product. Such facilities are required for the investment in ships, submersibles, and sensor systems to pay off.

7. OTHER NEEDED TECHNOLOGIES

- Improved battery technology to reduce size, weight and recharge times while increasing power and endurance.
- Quiet, simplified electric motors to replace the noisy, inefficient hydraulic thrusters now widely in use.
- Potted electronics for the elimination or reduction of pressure resistant housings.
- Miniaturization of sonar systems for deployment on smaller, lighter vehicles.
- Improved ballast control technology.
- Improved tether cable management systems.

TECHNOLOGIES SPECIFIC TO MANNED VEHICLES

A depth limitation system is needed that will automatically prevent a midwater submersible from exceeding its operational depth. At present, most such submersibles are not allowed to work in areas where total depth is greater than their operational depth limits, because of insurance. This has limited their use to coastal waters. Development of a reliable depth-limiter will greatly enhance the utility of midwater submersibles by expanding their operating area from less than 10% of the world ocean to more than 90%. The design and testing of such a system do not present a major engineering challenge. Similar constraints also affect the midwater use of chiefly benthic submersibles such as ALVIN, PISCES V, and TURTLE.

TECHNOLOGIES FOR AUTONOMOUS SYSTEMS

Autonomous vehicles have the potential for providing new types of observations and for providing more data at less cost. Developments are required in several areas to realize this potential.

Pragmatic improvements are required to basic vehicle systems to permit reliable, unattended operation over periods of weeks or months. Subsystems from manned submersibles or ROV's, such as power and propulsion, must be extrapolated to the unique demands of the AUV problem. Long-term sensor reliability and calibration problems must be solved. Fouling by organisms and sediments must be dealt with.

A variety of computational issues must be addressed to make autonomous vehicles a reality. While the first operational autonomous vehicles will probably perform tasks that are substantially deterministic, the full potential of autonomous vehicles requires that the vehicle respond intelligently to incoming data. A variety of computational paradigms for mobile robots are emerging and should provide an appropriate framework for such systems.

ASSESSMENT OF MANAGEMENT ISSUES

Our assessment of research needs and of submersible technologies have shown us that the scientific justification for expanded facilities support is very strong, and further, that the majority of necessary technological capabilities already exist, albeit not generally within the scientific community. What is needed by the oceanographic research community is access to this new technology.

To deal with these problems we are recommending a relatively small, but critically important reorganization of the facilities support structure. These changes are designed to improve access to the tools necessary to conduct research, but without the imposition of new layers of bureaucracy for the scientists to struggle against.

What follows is a discussion of the principal management issues:

1. The roles of the federal agencies.
2. Issues concerning ALVIN operations.
3. Gaining access to depths beyond 4 km.
4. Gaining access to shallow-depth vehicles.
5. The creation within UNOLS of a committee to oversee and implement the integration of submersible technologies.

BACKGROUND AND CONTEXT

The support structure within the U.S. for academic research and development is extremely diverse and decentralized. It ranges generally though public, private, institutional, local, state and federal levels. At the federal level it is represented by a mosaic of agencies and programs, all of whose missions are to some extent distinctive, yet in some ways overlapping. The diverse missions are made distinctive by various combinations of needs and criteria, be they: disciplinary, end-product, basic research, applied research, technology development, engineering, or educational. As one looks inside the overall mosaic at the level of a given discipline, such as marine science, the diversity continues at the smaller levels. This diversity also continues at the even smaller levels pertinent to this report, i.e., the development of appropriate submersible technology and its effective use in academic marine research.

The diversity of this support structure is in some ways a great strength. In other ways it presents real difficulties which represent a significant weakness. The strengths tend to develop within relatively narrow areas of focus. A good example is the NSF support of individual basic research projects in the disciplinary program areas. The weaknesses tend to show up either in the areas between foci, or in those areas where technological evolution necessary to the development of research methodology, occurs outside the discipline and then must be incorporated to effectively fulfill a credible mission. These general strengths and weaknesses tend also to repeat themselves as one views the system at more detailed levels. It is important to realize that the weaknesses are tending to become more evident and harmful as science evolves, as scientists demand more resources, and as society demands strong connection with their needs. This is particularly so for marine science which is extremely diverse, has intellectual connections with most of the basic and applied disciplines, has important societal applications -- long and short term -- in a wide variety of areas, and is more dependent on technology than most fields.

FEDERAL MANAGEMENT STRATEGIES

Each of the three federal agencies (NSF, ONR, NOAA) should maintain separate programs for providing submersible research facilities. Like the research fleets which have evolved to meet the particular needs of each agency, we can expect that submersible utilization patterns will also continue to develop according to the different needs of each agency.

There are several good reasons for avoiding centralization of these facilities:

- This is a rapidly advancing technology which will greatly expand the diversity of user options.
- Current demand for submersible time already exceeds the available federal facilities.
- Demand from researchers is expanding.
- Use patterns are divergent.

While the three agencies' submersible facilities support programs should remain separate, there should be a centralized oversight group to:

- coordinate scheduling,
- act as inter-agency liaison,
- help to avoid duplication of effort,
- coordinate shared-use tools and instrumentation,
- promote the development of tools and instruments,
- develop and provide oversight of safety and performance standards,
- develop facilities management procedures, and
- help to develop shared-use of international submersible facilities to support science.

NATIONAL SCIENCE FOUNDATION

While both ONR and NOAA have operated a variety of submersible systems in support of research, NSF has limited its support almost exclusively to ALVIN for the last 25 years. NSF very much needs to expand its access to a broader range of facilities for submersible-based research.

NSF should solicit proposals from UNOLS ship operators, including NURP programs (or possibly the private sector, with NSF's Division of Polar Programs ship operations contracts as a model) for grant or contract support to serve as agents to provide leased submersible facilities to principal investigators of research projects.

Once awarded, funding should be handled with OCFS and within the operating institution as if the submersible program was just an additional element in a multi-ship operation.

We suggest starting with one such institution on each coast, then considering expansion to include other operators after 2-3 years if needed.

The level of support for this activity from OCFS would be determined (like ship time) by the amount of submersible time requested in research grants funded by OSRS. We believe that an appropriate amount for NSF to budget for start-up of this effort is $2 million annually (less than 10% of the NSF ship operations costs.)

Funded research projects requiring submersible time would be scheduled as part of the UNOLS scheduling process on the most appropriate support vessel, regardless of its operating institution (i.e., not necessarily on ships of the contracting agent institution).

Once it is up and running such a program should be able to function as part of an existing UNOLS facilities support operation with just two additional administrative positions: an associate marine superintendent and a secretary.

Decisions on which research proposals to fund and field should be made exclusively by OSRS and OCFS, not by the operator.

Just as we trust the principal investigators to select the most appropriate ships for their cruise needs (subject to adjustment by the peer review and scheduling processes), we must also let them select the best submersible system for their research needs (subject to reasonable constraints).

Submersible equipment would be leased from commercial operators or foreign research institutions, subject to rigorous safety and performance standards.

A principal responsibility of the operating institutions will be to develop and maintain a broad continuing knowledge base about the available submersible systems and their capabilities.

Oversight responsibilities for this process would be vested in a Submersible Science Committee, created by UNOLS, and operated as an adjunct to the ALVIN Review Committee.

Principal investigators would treat submersible system requests just like ship time requests, with a form akin to the standard 831 ship time request, that is included in research proposals.

Submersible system lease costs would not be included as line items in NSF research budgets.

Research proposals requesting submersible facilities use would be reviewed through the standard peer review and panel sequence according to their scientific merit. Funded projects would be allocated ship and submersible time thorough OCFS and UNOLS scheduling procedures.

Selection of the most appropriate submersible system should be based on vehicle characteristics and scientific capabilities established by the principal investigator of the research project.

We believe that NSF cannot rely on NOAA/NURP to provide for the majority of its non-ALVIN submersible needs, for several reasons. In the first place, the demand for submersibles to support NOAA projects is already far greater than NURP can support. Interagency obligation cannot be guaranteed because their budgets are not coupled. The different agencies have different missions and research priorities, (e.g. applied vs basic research). Likewise, NOAA has been far more subject to politically motivated priorities, as evidenced by the geographical imbalance in the NURP program and by zero-level funding. While the two agencies should certainly work together in order to coordinate their submersible operations, NSF cannot look to NOAA to solve its needs for providing researchers with access to shallow-water submersible facilities.

OFFICE OF NAVAL RESEARCH

ONR should make SEA CLIFF, TURTLE, NR-1 and DOLPHIN available to the civilian research community on a regular basis, as frequently as possible. This process should include a timely request for proposals, proposal evaluation through a peer review process, and a reliable commitment to support the selected projects within the constraints of the Navy's operational priorities. Toward this end, ONR should establish links to the civilian research community through UNOLS and the proposed Submersible Science Committee, to facilitate efficient use of these vehicles.

ONR should upgrade the tools, equipment and instrumentation of TURTLE and SEA CLIFF to a level consistent with current research needs and ALVIN equivalence.

ONR should assign two civilian resident technicians to provide some badly-needed continuity in the interface between civilian research users and the military operational crews of SEA CLIFF and TURTLE. These technicians could also provide a valuable interface with the ALVIN group.

ONR should establish mechanisms within its contracting procedures (similar to those suggested above for NSF) to facilitate the lease of commercial submersible facilities (especially shallow-water systems) for use by ONR research contractors.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

In general, we agree with the recommendations of the Jennings Committee, which recently examined the role of NOAA's Undersea Research Program (NURP) in the context of agency needs and national research needs.

Of particular significance, the Jennings Committee recommended that:

- NOAA should provide research funding as well as facilities support.
- NOAA should now begin planning, and development for the construction of a deep-diving (> 6,000 m) submersible by the early 1990's.

To these recommendations from the Jennings Committee Report, we add the following:

- NURP must establish regional programs on the West coast and the Gulf coast.
- Regional NURP programs should become members of UNOLS and participate in the scheduling process.
- NURP should change its restrictive policy against the use of one-person submersibles.
- NOAA should follow the program development strategy suggested by the Jennings Committee.

ALVIN

The ALVIN program gets high marks for providing a safe and effective tool for deep sea research. ALVIN's effectiveness has been greatly enhanced by its conversion to a single point lift, by the replacement of LULU with the ATLANTIS II, and by its new control and propulsion systems. Likewise, recent changes in personnel policies for pilots and technicians are an appropriate first step to help reduce the rapid turnover problems that have periodically hampered the program and negatively affected its science. However, there are continuing needs for technological improvements and crew expansion in order to raise the efficiency of the system to meet the scientific and technical demands that will be placed on it over the next 10-15 years.

Among ALVIN users there is widespread dissatisfaction with the suite of tools, instruments, cameras and lights that are presently available. The consensus is that in most cases these assets are obsolete and are often unreliable. The next major effort of the ALVIN program should be to upgrade these subsystems to match the high quality and dependability of the primary system.

Of particular concern are data logging, video systems, sonar systems, navigation, and Seabeam. Seabeam data acquisitions should be a standard function during most ALVIN operations (and thus not borne as costs to research grants). However, the data processing costs should continue to be supported by individual grants. The committee also believes that ALVIN should be equipped with an integrated, real-time navigation and high resolution scanning sonar system. There is as well, a need for improvements and for greater reliability in the datalogging system. Lastly, the video imaging and lighting systems are seriously inadequate and far below current state-of-the-art for underwater applications. These systems require immediate upgrading.

The ALVIN operations group, both seagoing and shore-based, has done an exceptional job of making the submersible a safe and effective scientific tool for deep ocean exploration. ALVIN and its operations and capabilities have long been used as standards by which other submersible operations are measured, and rightly so. ALVIN has carried out complex dive programs, sometimes under difficult weather and logistical conditions, with only minimal loss or no loss at all of dive time.

The committee does see, however, that the ALVIN operation has continued to function within a financial budget that limits the potential for growth and which has begun to impact the efficiency and accuracy of scientific programs. Given the high-level of projected future use for ALVIN, and the need for technical precision and advances in the types of sensors available on the sub, we feel that the following material and personnel matters have an urgent priority.

The ALVIN shorebased and seagoing technical group must be expanded to meet the future needs of the science community in an effective way. At present, the rate of turn-around of pilots and the need for ALVIN systems upgrades (optical, acoustic, navigational, datalogging) warrants increases in personnel to two full teams, and increased overall funding of the ALVIN program in order to meet the scientific and technical demands of deep ocean sciences in the coming years and decades – into the 21st century.

We have identified below some key areas of future needs that will impact both the technological and personnel requirements of the ALVIN group. These topics include both present areas for improvement to optimize scientific output from ALVIN diving, as well as possibilities for near-future upgrades to increase the precision, accuracy and capabilities of the ALVIN system.

DATALOGGING

The datalogging capabilities on ALVIN have improved in the recent past, but we still see a significant need for improving the reliability of this critical sub-system. The datalogger now automatically records: time, corrected-depth, altitude, heading (from the gyro compass), conductivity and temperature. This system should also include speed, and should be independent of the datalogging system for the vehicle's electronic and hydraulic monitoring devices. However an onboard back-up system, identical to the main datalogger could be used to monitor the vehicular systems. The electronics and programming format should permit easy input from at least 2-3 other, occasionally used sensors (e.g. magnetic gradiometer, gravimeter, water chemistry sensors, high-temperature thermistor, etc.), and should be menu-driven to allow the data to be manipulated and processed immediately post-dive by the scientist divers.

NAVIGATION

It is important that ALVIN be equipped with an integrated real-time navigation and high-resolution scanning sonar system. This system should include iterative range and bearing input from the existing long-baseline system, as well as a short-baseline acoustic transponder system, with real-time data-logging and display of sub position "in-the-ball" on a reliable computer monitor. In addition, the system should permit overlaying the ALVIN track on both Seabeam base-map data as well as real-time, high-resolution bathymetry acquired with the existing topographic sonar, as ALVIN is flying over the seafloor in a survey mode. This system should be automatic, in the sense that sub positions are displayed every 5-10 seconds and recorded, digitally into a total-system datalogger.

OPTICAL AND ACOUSTIC IMAGING SYSTEMS

A recurring camera problem is that the dataframe on the 35 mm camera has not functioned properly. This has seriously affected a number of dive programs. The dataframe inputs should be more integrally tied to the future datalogger inputs so that compass heading is based on the gyro rather than magnetic compass (for more precise structural measurements from photographs). The depth and time information should also be synchronized with the datalogger time base and inputs so visual observations, position, and images can be accurately and easily correlated.

Ideally the SIT video should monitor the bottom terrain characteristics from a higher vantage point, thereby giving scientists a broader morphological and structural perspective of the seafloor. With the advent of electronic still imaging systems that give very high resolution (14 bits), digital images of the seafloor from altitudes of between 10-15 m, this technology should also be made part of the ALVIN imaging systems.

The acoustic imaging system on ALVIN has always consisted of a standard CTFM obstacle avoidance sonar. This system has been excellent for avoiding obstacles, but is limited in its effectiveness to give scientists an acoustic image of prominent structural features along the submersible track that they can use as part of the dive database. Recently, a down-looking, topographic sonar has been added. ALVIN should also be configured with high-frequency (100 kHz) side-looking sonar transducers so that it can also carry out larger-scale mapping work during the course of a dive or dive sequence. Furthermore, the coupling of the electronic still photographs and the side-looking acoustic imaging would significantly enhance ALVIN's ability to conduct state-of-the-art mapping and would help place the dive observations into pre-existing detailed bathymetric or Sea MARC type side-looking sonar databases.

SEABEAM OPERATIONS

ALVIN seagoing personnel should be trained to help run the Seabeam sonar so that the system can be supported with only one NECOR URI/GSO Seabeam technician. Conversely, we see an excellent opportunity for the URI Seabeam technician to provide assistance to the ALVIN seagoing group in such areas as integration of navigation systems, computer hardware/software upgrades and maintenance, and electronic repair.

The committee believes that Seabeam data acquisition should be block-funded on ATLANTIS-II so that all ALVIN diving programs can benefit from the system's capabilities for surveying, navigation, dive relocation and nighttime ancillary investigations. Data processing costs should be requested by individual scientific investigators and the justifications for additional processing beyond what can be carried out while at sea, should be based on a strong scientific merit.

GAINING RESEARCH ACCESS TO DEPTHS BEYOND 4,000 METERS

INTRODUCTION

One of the principal recommendations of the Jennings Committee Report (1986) was that the U.S. must extend its deep diving research capability, through the development of a 6-7,000 m submersible by the mid-1990's and a 10,000 m vehicle by the end of the century. This is still good advice, and the need for U.S. deep-diving capability has been made even more compelling by recent advances in the deep submersible programs of other nations. The costs of these submersibles, including their dedicated support vessels were estimated by the Jennings Committee to be $45 million and $75 million respectively. Because of progress in materials research and innovative engineering design studies, the costs of such a vehicle may be significantly less than estimated in 1986.

The only operational 6 km submersible in the U.S. is the Navy's Deep Submergence Vehicle SEA CLIFF. To date SEA CLIFF has been available to the civilian research community only on a very restricted basis. Its effectiveness and reliability have been severely hampered by the lack of an adequate support vessel, by the rapid turnover of support personnel and pilots, and by the lack of modern scientific tools and instrumentation.

The potential for improving this situation has changed for the better during the past two years with the acquisition and refitting of a leased support vessel, the M/V LANEY CHOUEST. Likewise, directives from the Secretary of the Navy have made a limited provision (up to 60 days/year) for civilian research utilization of SEA CLIFF. It remains to be seen, however, how available SEA CLIFF will be for scientific operations and the extent to which this submersible, its support ship and their respective crews can efficiently carry out science-based seafloor investigations and sampling.

Despite this welcome improvement, there is a growing feeling among U.S. scientists that SEA CLIFF offers at best only a stop-gap solution for the problem of providing deep seabed research access in the 1990's, because the demand will soon surpass SEA CLIFF's limited availability.

INVENTORY OF DEEP (4-6 KM) SUBMERSIBLE ASSETS

At the present time there are only five operational submersibles in the world, capable of reaching a depth of 6 km:

- SEA CLIFF (U.S. Navy, DSV-4) was built in 1968 as a military counterpart to ALVIN (DSV-2), with the same general configuration and operational capabilities. In 1983 its original pressure sphere was replaced with one of titanium to give it an operating depth of 6 km. It is operated by the U.S. Navy and in the last decade has been only occasionally available for civilian research use. It has not been operated consistently in the 4-6 km depth range. It has not yet had an effective impact on the needs of the academic research community.

- NAUTILE (French) was launched in 1985 by IFREMER for commercial applications as well as for research. It holds a crew of three in a titanium pressure sphere with an operational depth of 6 km. It has been used by a few U.S. scientists working in cooperation with French investigators in transform fault regions of the sea floor, ridge crests and hydrothermal vent areas, and in the western Pacific regions. It is also available for lease with its support vessel NADIR, from IFREMER. NAUTILE carries state-of-the-art video and photographic systems, as well as advanced sonar systems, manipulators and instrumentation. NAUTILE has been operated successfully and continuously in the 4-6 km depth range.

- MIR I and MIR II (Russian), in December of 1987 two 6 km research submersibles were launched by the Finnish Company, Rauma-Repola. Both vehicles were delivered to the Soviet Academy of Sciences. They are twice as fast as any other deep submersible (5 kts), with twice the battery power and a steel alloy sphere that holds a crew of three. Both submersibles have paired manipulators and a full set of tools and precision instrumentation. These subs were successfully used during summer, 1988 in joint US/USSR field work in the North Atlantic. They are deployed from the dedicated support vessel AKADEMIK KELDYSH and are reportedly available for lease to U.S. researchers. Operations in U.S. waters are scheduled for 1990.

- A fifth deep research submersible, Japan's SHINKAI 6500, was completed in 1989 and conducted sea trials in early 1990. Like SEA CLIFF and NAUTILE, it has a titanium pressure hull and a crew of three. This vehicle is capable of operational depths to 6.5 km and is operated by JAMSTEC from the dedicated support vessel YOKOSUKA.

SCIENTIFIC NEED

ALVIN's 4 km depth range has brought roughly half of the world's benthic regions within the reach of U.S. researchers. A 6 km depth range nearly doubles the coverage, such that 98% of the sea bed is accessible. The regions of the sea floor that are beyond ALVIN's reach include the deeper portions of continental margins, deep sea trench slopes and some trench floors, deep ridge crests and many ridge flanks, transform fault zones and fracture zones, and abyssal plains. We have described in a previous section of this report, the compelling scientific justifications for conducting submersible science in these regions, the largest unexplored geological features on our planet.

At present, the demand by U.S. scientists for 6 km research capabilities is limited by artificial constraints. Researchers with interests in oceanographic processes or benthic features that extend beyond ALVIN's 4 km depth range, know that currently their chances of ever getting dives to those depths are minimal. As a consequence investigators are not willing to waste their time in requesting this kind of facilities support. There is good science to be carried out in the 4-6 km depth range, but U.S. scientists do not presently have any 4-6 km manned submersible facilities reliably at their disposal. Unmanned systems may have substantial near-term impact on some scientific requirements. Systems like ARGO/JASON, RUM III and HYSUB are securing a niche at depths up to 6 km for research which does not require manned presence.

Based on the present demand for ALVIN and the apparent directions of ocean research discussed elsewhere in this report, we can predict the need for full utilization of both ALVIN and a 6 km system by the end of the 1990's.

OPTIONS

Given the scientific justification and the growing need for deeper access, there are several possible ways to proceed. The chief problem with continuing to rely on SEA CLIFF for access to depths between 4 km and 6 km is that this approach ignores the growing demand within the research community for increased access to these depths. This situation perpetuates an artificial constraint on the natural development of deep-sea research.

Since 1986 the Navy has agreed to make 60 days of SEA CLIFF and/or TURTLE (DSV-3) time available each year for use by civilian researchers. So far, this objective has not been realized. Even those scientists actually scheduled to use a Navy DSV have had their cruises delayed or cancelled, often with no realistic opportunity for re-scheduling. In general, civilian research use of the Navy-operated DSV's has been inadequately supported by ONR and not supported at all by NSF. This situation is of course understandable, because the principal missions and highest priorities for these vehicles are military.

The result, however is that civilian research access to depths between 4 km and 6 km is severely restricted, and SEA CLIFF has not yet proved to be a viable facilities option for most deep research needs.

For this and other reasons there is considerable skepticism among civilian researchers regarding future SEA CLIFF operations, and a general assumption that SEA CLIFF represents a national research facility only on paper.

OPTION 1. Expand and improve civilian research access to SEA CLIFF – In 1988 the Navy leased a first-class support vessel for SEA CLIFF that has a single-point lift system and a Seabeam mapping system. This is a genuine improvement in operational capabilities that should enhance SEA CLIFF's utility, at least until mid-decade (when the lease expires). For a significant improvement of research capabilities however, several additional steps are necessary, including the acquisition and development of a suite of modern tools and instrumentation for the program that is at least on a par with those available for ALVIN and the other deep subs.

A characteristic problem of SEA CLIFF and TURTLE operations is the frequent turnover of key personnel in Submarine Development Group One. The result is a lack of continuity that does not exist in the ALVIN program and, we believe, that has a profound negative impact on the quality of the program. An appropriate solution would be to hire two or three civilian technicians (in addition to the Navy personnel) to serve as a continuing scientific interface between Submarine Development Group One and the civilian research community.

OPTION 2. Lease Option – One way to meet the growing demand for access to the 4 km to 6 km depth range is to lease foreign submersibles. NAUTILE is available on such a basis, as are MIR I and MIR II. Rauma-Repola of Finland is considering the construction of a third 6 km submersible that would be made available for lease on a competitive basis. JAMSTEC, which operates the SHINKAI 6500 is also considering the possibility of leasing their vessel to other nations. At present there are no established day rates available for any of these submersibles, but common sense and the knowledge that ALVIN and ATLANTIS II cost roughly $25,000/day suggests a bottom line of approximately $30,000. For the foreseeable future, the only way for U.S. scientists to gain access to depths greater than 4 km with modern technology, will be to lease a foreign sub.

OPTION 3. Rebuild TURTLE – In 1971 ALVIN was rebuilt with a new pressure sphere that increased its operating range from 2 km to 4 km. In 1983, SEA CLIFF was rebuilt with a depth range extension from 2 km to 6 km. TURTLE is still using its original pressure hull with a depth rating of 3 km. A conversion of TURTLE would be less costly than new construction and might prove to be the most efficient way to increase civilian research access to 6 km, and to expand the Navy's deep submergence capacity as well. An alternative would be to provide ALVIN with a 6 km sphere and replace TURTLE's 2 km range with ALVIN's present 4 km sphere.

OPTION 4. New construction – This could take place along several lines, depending on the balance of funding sources. The first step would be conceptual design studies based on projected science mission requirements. This step could be initiated by a potential operating institution, by a select subcommittee of the ALVIN Review Committee, or by a federal agency. A legitimate question in this context is whether or not the U.S. retains the industrial capability to build our own 6 km manned submersible, at a reasonable price.

An alternate mode of new construction would be to utilize an "off the shelf" design, built to conform, as well as possible, to meet U.S. mission requirements and safety standards. Rauma-Repola, for example, is prepared to build a third DSRV-6000 to order, for approximately $25 million. JAMSTEC and IFREMER could also lean on recent experience and contract for the construction of new vehicles based on tested predecessors. While new construction by the U.S. might take five years of more, foreign construction of existing designs could cut the delivery time in half.

OPTION 5. Alternative technologies – The most appropriate answer for the need to extend our research capabilities into deeper water may not be the most obvious step. The successful application of acrylics in shallow-depth vehicles has led to a re-examination of materials such as plastics, glass and ceramics as light-weight, transparent substitutes for titanium and steel in deep submersibles. Materials science and other emerging technologies hold real promise for the next generation of manned submersibles but some of these advances may not be practical alternatives until the end of the 1990's.

OPTION 6. Unmanned Systems – The scientific ROV with an armored, fiber optic cable that delivers both power and high bandwidth telemetry is currently evolving and has been operationally verified to depths of 6000 meters. These types of systems represent viable possibilities for operation below 6000 meters, as all of the elements can be extrapolated to greater depth, with slightly reduced efficiency. Limited mobility and substantial surface support requirements are weaknesses, but high bandwidth and large amounts of power and endurance are clear advantages. Acquisition of an operational fiber optic cable and a winch that could support different kinds of towed and powered vehicles to full-ocean depth, will be necessary.

A very interesting alternative to the traditional towed or tethered vehicle is a self-powered vehicle with a small diameter lightweight tether that supplies only telemetry. Compared to a traditional ROV, such a vehicle could have similar bandwidth (it might be restricted to one fiber), but could have improved mobility and reduced surface support requirements. The deployment and recovery techniques and dynamics of the long, lightweight tether must be examined and understood, but preliminary analysis indicates this approach is quite feasible.

The best way to push the evolution of appropriate technologies to gain deep-sea access may be to develop a new generation of deep diving, unmanned submersibles. Such a vehicle could be battery powered to eliminate the many constraints imposed by tethers which supply power from the surface. Improved power/weight ratios from new kinds of batteries and reduced power demand without life support requirements make a self-powered vehicle a practical option. At the same time, real-time control and data acquisition can be maintained with fiber optic links or with pulsed acoustic links. These are areas where U.S. technology can make a real contribution because of its particular engineering strengths in communications, robotics and high level control (artificial intelligence). Areas that will require development but where breakthroughs are near, include batteries, telemetry, instrumentation, and pressurized electronics.

There are certain fiscal advantages to this approach. We would gain a limited degree of access to the deep-sea floor for less than the cost of a manned vehicle. The operating costs would also be much reduced. There would be no need for a dedicated support vessel, instead the vehicle could be deployed from a number of our larger research vessels.

DISCUSSION

Given the logical priorities of the Navy's deep submersible program and the past two decades of rare utilization by the science community, it is difficult to be optimistic about SEA CLIFF meeting the growing needs of the research community in the 1990's. We support the recommendation of the Jennings Committee that the U.S. should not delay in its development of a 6-10 km research diving capability. However, since NSF, ONR, and NOAA appear to be unwilling to even address the development of a new generation of deep-diving, manned vehicles, we believe that the best alternative strategy would be to: (1) encourage the Navy and other U.S. funding agencies to annually make at least 60 days of SEA CLIFF time available and worthwhile (i.e. provide science funding, provide adequate tools and sensors, insure pilot training and effectiveness for science operations, etc.) for U.S. scientists by no later than 1991; (2) when the needs for deep access exceed SEA CLIFF's available time or capabilities, we should lease foreign submersibles for science in the 4-6 km depth range; and (3) develop an unmanned system that would promote state-of-the-art technological development (i.e., a new generation of optical and acoustic sensors, rapid data links, multi-sensor capabilities, sample or payload recovery/deployment options; and (4) continue this technological evolution into a manned system.

In these circumstances the question of the effectiveness of manned systems vs unmanned systems is not considered to be an issue. For work at depths beyond 4 km, manned systems are inherently more flexible and more capable, albeit more expensive. Within the operational limits of unmanned systems however, a significant fraction of the projected deep benthic research needs can be met. If the U.S. were to successfully develop such an unmanned vehicle our deep, manned submersible needs for the 1990's might be met by trading time on our unmanned system for time in foreign manned vehicles.

An alternative approach to this question may be to design the vehicle such that personnel capsules can be added on a modular basis, when real-time control or direct intervention and observation are required. The basic vehicle would be configured to operate in either a manned or unmanned mode. In concept, such vehicles take advantage of all the technologies mentioned above for unmanned systems. They differ only in adding self-contained personnel capsules. In this approach, only the capsules need to be man-rated for operational depths. This approach offers the considerable advantage of human intervention and full, real-time control without the large size and complexities associated with conventional manned vehicles. It is reasonable to consider the sequential development of a deep-diving system which first operates remotely as proof-of-concept, then incorporates manned capabilities with the addition of deep-rated personnel capsules.

PROVIDING ACCESS TO SHALLOW DEPTH VEHICLES

With regard to vehicles operating at depths of about 1 km or less, the committee believes that leasing is the most cost-effective approach.

The development of technology to work at moderate depths in the ocean has occurred largely in the private sector, to meet the needs of the offshore oil industry. Only in recent years has the scientific community begun to use these tools. The results have been strongly positive and demand for access to them is growing rapidly. The two principal impediments to using this equipment in grant supported projects have been the difficulties of (1) surviving the peer review process when the costs of contracting for the submersible must be included as line items in proposed research budgets and (2) dealing with two separate programs -- one for research support and the other for facilities support. There are no established procedures within NSF, ONR or NOAA to make the contracting process as straightforward as the scheduling of a UNOLS ship. This situation must be changed and the three agencies should work together to facilitate the change.

The NOAA/NURP Center at University of Connecticut, Avery Point has repeatedly demonstrated the value of the leasing concept to provide NOAA researchers with access to specialized submersible research facilities. Recently, the center at the University of North Carolina, Wilmington, and (until 1990) the Fairleigh-Dickinson University center at St. Croix have followed suit. The principal problem with the national (NURP) program is that West Coast researchers are virtually disenfranchised, with no real regional program and thus no access to these facilities. While the national office has begun to deal with this problem, lack of funding has prevented a solution. This situation is a major flaw of the program which urgently requires corrective action by NOAA and its parent, the Department of Commerce. Dealing with this situation should involve NSF and ONR as well as NOAA, with the goal of increasing overall federal support and developing inter-program support mechanisms such as UNOLS. At the present time there is no effective coordination between NSF, ONR and NOAA/NURP, in this regard.

To deal with the problems of providing access to shallow depth vehicles, the committee makes the following recommendations, which follow closely the current procedures of each agency, and call for little or no re-organization.

At ONR, shallow-water submersible contract costs should be budget line items, just as ship costs are handled now. Oversight of contracts, safety standards and insurance would be handled by a UNOLS Submersible Science Committee.

At NSF, requests for submersible facilities support should also be handled like that agency's ship time requests. Research proposals should contain facilities requests like the 831 form for ship time, with details on the specific system requirements. Contracts for submersible systems would be funded by OCFS through an appropriate UNOLS ship operating institution (or by a private contractor or NOAA/NURP), again with oversight to strict safety and operational standards by a UNOLS Submersible Science Committee.

NOAA's Undersea Research Programs are already well along in their development of leasing programs to meet the agency's needs. However, there is a critical need to provide geographic balance to the national program, first with the establishment of one or more functional West Coast Regional centers and then one on the Gulf Coast.

The committee also recommends that NOAA's NURP Centers should join UNOLS as full participating members, to bring their experience to the rest of the community and to become involved in scheduling and the setting of operational standards. Thirdly, the committee agrees with the recommendations of the Jennings Report that NURP should provide expanded support of research, as well as support for facilities. At the present time, NURP policy precludes the use of one-person, ADS submersibles. NSF has supported several successful field programs with these vehicles. We believe that NURP policy in this regard must be changed, and further, that NSF and ONR should not be constrained by this misguided attitude, should the NURP policy not be changed.

In each of these cases, the principal investigator will not have to re-invent the wheel each time he or she needs a submersible to conduct research. Rather, support for submersible facilities could be handled matter-of-factly, like agency requests for ship time or other facilities – and science will become the driving force – not facilities. The keystone of these recommendations is the creation of a new UNOLS committee, the Submersible Science Committee, to help meet the program needs of all three agencies.

ESTABLISHING A PERMANENT SUBMERSIBLE SCIENCE COMMITTEE

The most important recommendations of this report addresses the continuing need for the kind of effort that this committee has conducted. In order to implement the present committee's findings and to facilitate the integration of submersibles other than ALVIN into the oceanographic research community, there is a clear need for a permanent Submersible Science Committee (SSC) within UNOLS. In our view, the most appropriate action would be to make the SSC a sister committee to the ALVIN Review Committee. Such a group should be established as soon as possible.

The role of the UNOLS Submersible Science Committee would include:

- establish guidelines and provide oversight for contracting, safety, and insurance for (foreign and domestic) leased submersible systems,
- establish basic operational standards for leased and owned systems,
- coordinate and promote the efficient joint scheduling of ships and submersibles on an inter-agency basis,
- assist the Navy in developing coordinated civilian user programs for SEA CLIFF and TURTLE,
- monitor and promote the development and application of appropriate new technologies for submersible science,
- establish and coordinate a shared-use equipment pool and tool inventory,
- advise NSF, ONR, NOAA and other federal agencies on submersible technology, its evolution and applications, and
- develop procedures for facilitating access to submersible systems by principal investigators of research proposals.

There are several ways that a permanent SSC could be established. One approach would be to simply make it a subcommittee of the ALVIN Review Committee (ARC) with the task of dealing with submersible issues "other than ALVIN." We believe however, that this structure would be inappropriate. First, because it could easily encumber the ARC, which is nearly overloaded already; and second, because this structure would constrain the necessary evolution of the SSC in response to the growing needs of the submersible user community. Within 5 years, we expect that the SSC will be working with many more research projects than the ARC.

Another approach would be to take the opposite tack, and to anticipate the widespread use of submersibles throughout oceanography by the end of the decade. In this approach the ARC would become a subcommittee of a larger SSC, which would also have subcommittees for shallow-depth submersibles, deep-diving (> 4 km) vehicles, and technological developments. The problem with this approach is that it may be premature.

The evolution of these changes in submersible utilization patterns will take from 3-5 years at the earliest, and an abrupt re-structuring might not be suitable.

We believe that the Submersible Science Committee should be established by UNOLS as a sibling of the ALVIN Review Committee. In this mode, it would have enough independence to respond directly to the needs of the user community, yet would be linked to the ARC so that it could readily provide information for technology transfer and research developments to ARC and UNOLS.

A major distinction between the SSC and the ARC, however they are configured, is that the SSC will not review proposals for appropriateness or for scheduling purposes as the ARC does. Because the ARC is managing a single facility, this practice is necessary. For the SSC however, the focus can be to facilitate the use of submersible technology – not its regulation.

The principle issue is not how the Submersible Science Committee comes into being, nor even how it is initially structured. Regardless of these questions, the need for the SSC and the roles it must play are very clear, and the most important issue is to get it started.