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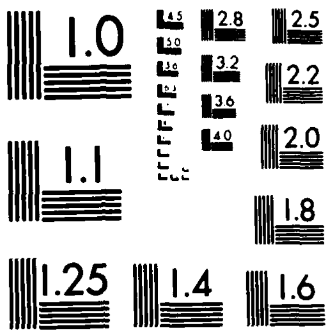

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Nav... Range... Deep Ocean Technology

An Assessment of Current Development, Forecasts, and Research Thrusts

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NAVY LONG-RANGE DEEP OCEAN TECHNOLOGY: AN ASSESSMENT OF CURRENT DEVELOPMENT, FORECASTS, AND RESEARCH THRUSTS

Proceedings of a Workshop
September 23-24, 1982
Washington, D.C.

Panel on Civil/Navy Ocean Engineering
Marine Board
Commission on Engineering and Technical Systems
National Research Council

National Academy Press
Washington, D.C. 1983

NOTICE: The project that is the subject of these proceedings was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the panel responsible for conducting the reviews and the workshop were chosen for their special competence and with regard for appropriate balance.

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These proceedings represent work supported by grant number N00014-82-G-0032 between the Office of Naval Research and the National Academy of Sciences.

Copies available in limited quantity from:

Marine Board
Commission on Engineering and Technical Systems
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

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SUMMARY

The Panel on Civil/Navy Ocean Engineering of the National Research Council's Marine Board has reviewed the report, U.S. Navy Long-Range Deep Ocean Technology Evaluation, at the request of the U.S. Navy. These proceedings provide assessment of the Navy's report which should assist in the development of a Navy applied research program. The report addresses technologies considered by the Navy to be fundamental to the support of noncombatant ocean engineering and operations below a depth of 100 meters. These technologies are: energy systems and conversion; life support; propulsion and auxiliary machinery; materials and structures; nondestructive testing; geotechnics; sensors; data transmission and handling; cables; robotics; teleoperators, and work systems; command and control; navigation; system dynamic response prediction; load handling; and moorings. For workshop purposes, the technologies were distributed among five ad hoc groups under the headings: energy systems, materials and testing, data systems, control, and dynamics.

The workshop addressed the identification of major variances from the Navy's evaluation of the state of the art, forecasts, and research thrusts needed to fill technical gaps not likely to be addressed by industry-based, including available foreign, development. The summary table shown on pages 3-14 highlights the major deviations that were cited by the participants. Major comments and cautionaries are also noted. The summary notations for each technology are more fully explained in the corresponding section within the text which includes the complete Navy report.

Five ad hoc working groups under the panel's direction developed technology review papers which were used in the workshop along with additional inputs and information from other technical specialists both within and outside the Navy. Workshop participants assessed the reviews, introduced additional background material, and considered intertechnology relationships. The workshop was held September 23-24, 1982, at the National Academy of Sciences, Washington, D.C. The attendees are listed in Appendix A. These proceedings are a record of that workshop.

The Navy's evaluation report, which forms a basis of reference for the panel, does not contain quantitative information regarding the character of technology and associated hardware. The objective of the Navy report was to use general descriptive language. Therefore, the workshop participants could not be specific in quantifying their assessments of the Navy report in most technical areas. Some parameters and ranges are noted where the Navy text provides guidance or where committee or workshop participants were knowledgeable about specific objectives or limitations, such as ocean shelf depths.

TABLE 1 Summary of Workshop Participant Reviews

Technical Area	Major Exceptions to Navy Report	Comments or Concerns
Energy Storage and Conversion	o Disputes the general conclusion regarding high cost of fuel cells.	o Identifies significant safety-oriented development in primary batteries and in life cycle performance of nickel hydrogen and silver hydrogen secondary batteries. Identifies recent Swedish fuel cell development.
	o Agrees with forecast but emphasizes need for sharp observation of European and Japanese development of closed-cycle systems.	
	o No major exception to thrusts.	o Emphasizes need for attention to lithium thionyl chloride battery development, at least to follow industrial progress. Adaptability of underwater systems to a variety of closed-cycle power plants should be investigated. Other research suggested includes integration of energy storage as part of structural member design, need to better understand technology of pressure-compensated batteries, and battery cell failure management.
Life Support	o State-of-the-art technology permitting tether-free life support to 600 meters should be reviewed and new technology developed in atmospheric mixing, decompression techniques, oxygen supply and control, environmental hazard monitoring and control, temperature and humidity control, and hotel facilities.	o Agreement with Navy thrusts in decompression study, physiological standards, contaminants and electroshock criteria. Navy needs to establish a physiological basis for the elimination of inert gas in decompression and to develop emergency rescue techniques.

Propulsion and Auxiliary Machinery	o General agreement with Navy report.	o Navy-sponsored development will be needed. Deep ocean mining and the National Science Foundation's scientific coring programs should be observed for possible improvements in propulsion and platform control.
Materials and Structures	o Navy report does not address the state of the art in the following areas, (although the Navy does have proposed thrusts in some of these areas): fabrication and joining, repair, characterization of material properties and performance, capability to specify design criteria, design criteria, design procedures, and environmentally sensitive mechanical behavior. o General agreement with Navy forecast and thrusts.	o Encourages thrusts in using advanced high-strength metallic materials and materials improvements to reduce distortion; observation of industry progress in cables and lines encouraged. o Development of nondestructive testing (NDT) for nonmetallic materials, for materials in structures, and to predict service performance from NDT data is needed; structural design to improve use of NDT is desirable.
Nondestructive Testing	o No major exceptions taken with Navy comments on state of the art.	o There is a close relationship of Navy and commercial interests in this technology, except possibly in testing deep submergence vehicles.

Nondestructive Testing (cont'd)	o Navy forecast places more emphasis on the degree of diversity of commercial nondestructive test and evaluation (NDT&E) development. Agreement that several passive techniques will require Navy support for their application.	
	o Navy thrusts considered appropriate.	o Thrusts on data processing and pattern recognition should be directed toward specific NDT&E techniques. o Techniques to inspect large fixed structures using implanted internal sensors should be considered.
Geotechnics	o Group agrees with Navy state-of-the-art assessment but also discusses its limitations.	o Current depth capability for in situ seabed testing (700 meters) and coring (300 meters) is better than Navy apparently recognizes. o There is a diversity of in situ static measurement techniques not covered in the report. Soil characterization using geophysical and geological data is becoming more emphasized in industry. o Material characterization of silts is also a problem (Navy report addresses difficulties only with calcareous materials).

Geotechnics (cont'd)

	o Correlations exist for using penetrometer cone data for design; Navy suggests they still need to be developed.
o Commercial thrusts may not extend to Navy needs, such as incalcareous soil description for engineer use.	o Focus on developing a 12-meter cone penetrometer seems to be too limited; suggests considering remotely operated device that penetrates and measures engineering properties in the top 30 meters of seabed.
	o Foundation response and performance improvement, rather than only stability, should be sought in development efforts; analytical modeling should be extended to compare specific response (e.g., pore pressure, stress), not just general response.
o Efforts to develop means to modify the engineering properties of the seafloor over large areas are considered unlikely to be successful and would be very limited by the environment permitting such action. Modification of the seafloor over local areas is state of the art.	o Technologies to recognize and avoid poor seabed stability situations are suggested in lieu of modifying the seabed character, where possible. There is a need to develop an ability to characterize the properties of silt under different degrees of consolidation.

Data Transmission and Handling	o No major deviations or exceptions are identified by the working group in its assessment of the Navy report.	o Capabilities of acoustic telemetry systems are described, such as a 4,800 bits/sec Navy coherent signaling system and a 20,000 bits/sec French link for slow-scan television. o There is still an insufficient engineering data base on fiber optic cables. o Acoustic telemetry performance will probably improve by factors of 2 to 3; this will result from Navy, industry, and foreign efforts. o Course of development is uncertain in magnetic bubble data storage; recommended technology to follow is in semiconductor memory for intermediate data storage and laser disc storage for large data bases. o Thrust research is suggested to extend capability in cable-free data transmission and control, to achieve greater bandwidths and higher data rates, and to develop data compression techniques to maximize the use of limited capacity underwater communication channels.
Robotics, Teleoperators, and Work Systems	o No major revisions to the Navy report are suggested.	o In forecasting trends, the development of teleoperators likely will be evolutionary and slow without the infusion of Navy development.

Robotics, Teleoperators, and Work Systems (cont'd)		o Replacing divers with teleoperators would be a very ambitious objective. Supervisory control (mixing human and computer control) is promising for constrained bandwidth systems. o Comments on control, sensor, and display development but notes that specific system identification for research could not be made without a statement of the range of "typical requirements."
Sensors	o Exception taken to the Navy perception that scientific instruments frequently fail to produce data that can be used by engineers. Much improvement has been made in the last decade and, in general, instruments can provide higher resolution and accuracy than needed for most engineering. o Present developments in sensor technology are making large-scale improvement without fundamental breakthrough. o Following exception and addition to the Navy thrust are noted:	

Sensors (cont'd)	- The area coverage capability limit for optical survey is 2,000 to 3,000 square meters (e.g., NRL's LIBEC system), not the 50 to 100 square meters cited in the Navy report. - Diver physiological sensors will be required as well as sensors to detect the presence of hazardous chemical and nuclear sources and fields.	o Thrusts should consider engineering requirements, sensoring techniques, and field test programs to define acoustical, optical, and electromagnetic characteristics, affecting data transmission in the water column and related engineering activities. o Research in "acoustic detection" should consider full range of enhancement possibilities offered by hull-mounted and towed sonar systems.
Cables	o No major deviations from the Navy's report are noted.	o There is an inadequate data base for predicting cable performance, retirement criteria, and repair, and for preparing cable specifications.
Command and Control	o No major deviations from the Navy's report are noted.	o Only Navy participation will further development of adaptive control systems for deep ocean work; industry will not need similar depth capability and endurance sooner than the Navy.

Command and Control (cont'd)		o Suggested thrust areas are: - Supervisory control; - Command language improvement (improved macro language, using linkage to on-board modules, which provides objective commands rather than the present operator-fatiguing continuous guidance); - On-board, unmanned, remotely operated vehicle, closed-system error correction micro computer subsystem; - Reducing and combining vehicle-manipulator degree of freedom; - Tether-free systems; - Multisensor systems.
Navigation	o No major deviations from the Navy's report are noted.	o *Electrostatically suspended gyro systems* require long and involved calibration. While inertial systems are used in submarine applications, use in submersibles applications, use in submersibles is constrained by cost and other factors. Retransmission techniques are for special purposes only and are not commonly a commercial need.

Navigation (cont'd)		o Thrust area comments emphasize arctic capabilities such as under ice and high-latitude navigation, large area subsurface navigation (150-kilometer range), and accurate local navigation (for remotely operated vehicles or divers). o Concern about expensive miniturization; the usefulness of "various-mission" studies in defining procurement specifications. Global Positioning System coupling to subsurface units will require development and alternatives should be considered, e.g., acoustic Loran or Raydist. o Navy R&D with possible fallout value to deep ocean needs are: correlation sonar, Trident velocity sensor program, and mine-hunting navigation systems.
System Dynamic Response Prediction	o Arctic environmental effects should be considered in evaluating the status of technology and planning dynamic analyses activities.	o Gaps in the ability to predict dynamic long-term response of structures include lack of understanding of: - Directional spreading of waves; - Wave nonlinearities in higher sea states and fluid-structure interaction; - Long-term response of coupled systems, especially understanding of damping mechanisms; - Verification of calculations using data collected on site; - Fatigue life calculations based on long-term response.

System Dynamic Response Prediction (cont'd)		o Some short-term responses to surface waves are still poorly quantified, particularly involving prediction of coupled response of ship-crane-cable loads. o Real-time sensing of surface wave conditions, including direction, needs to be improved. o The environmental data base concerning wave spectra, direction, and currents is inadequate to support prediction analyses. o Training in crane operation is advised, possibly including simulation facilities if available.
	o The Navy may benefit from industry work (usually nonproprietary) in low-cycle and high-cycle fatigue directed to large, fixed and floating structures. to large, fixed and floating structures.	o Industry development may be expected in special systems for arctic operations and "upwave" sensing systems for real-time motion prediction. o Research needed to close the gaps in areas identified in the state of the art.
Load Handling	o General concurrence with the Navy's evaluation of the state of the art, forecast, and thrusts.	o A data base exists to assist in understanding the mechanical and structural properties of wire rope, but it has been little used.

Load Handling (cont'd)		o Knowledge about cable characteristics and mechanics is more advanced than indicated in the Navy report; refinement of analysis and test techniques is suggested. o In load control, research emphasis needs to be placed on validation of basic assumptions, environmental data, and performance.
Moorings	o An extensive review of the present technology base for moorings notes the differences between ship and oceanographic survey moorings and the problem areas in analyses and modeling. o No major differences in forecasted technology were cited. Thrusts were identified and discussed in detail.	o Accurate prediction of vibration response of a long, flexible cylinder in a current which varies in speed and direction with depth, cannot be done now. moorings and the problem areas in o Geographic limitations on mooring feasibility are not identified. o Commercial mooring design and practice is unlikely to contribute to Navy lightweight, rapid-deployment needs. o There is a need for ongoing support of mooring modeling and for a compendium of models for engineering user reference. Model simplification is needed. Practical "engineering type" models of designs should combine wind, geostrophic, inertial, tidal, topographic, and eddy effects.

Moorings (cont'd)

- Environmental testing of the longevity of mooring components needs to be emphasized to subject material to in situ or simulated biological and chemical conditions of a site.

- A Navy center for collection of mooring data, validation information, and experience is needed.

- Mooring component development should consider further work in fairings and deep sea anchors.

INTRODUCTION

The Navy requested the assistance of the National Research Council, through its Marine Board, to review and provide an assessment of its report, U.S. Navy Long-Range Deep Ocean Technology Evaluation. The Navy's evaluation stems from its concern about an assumption that could affect research planning: that much of the exploratory development needed for deep ocean engineering* for noncombatant operations over the next 20 years can be readily adapted from other Department of Defense programs or from industry-sponsored development, including foreign technical sources. During 1981 and early 1982, concurrent with the Navy's activity in preparing the deep ocean technology evaluation, the Chief of Naval Operations (CNO) initiated a study on the deep seafloor mission requirements to compare available and planned assets with present anticipated requirements, in order to identify and prioritize areas of deficiency in deep seafloor operational capabilities. The Navy's evaluation of 15 technology areas covered by their report, and the review provided by the Marine Board's Panel on Civil/Navy Ocean Engineering in these proceedings, will be compared with mission requirements, described in the CNO's study, to provide a basis for planning the Navy's deep ocean technology development program.

The specific charge to the Panel on Civil/Navy Ocean Engineering is to identify major variances from or agreement with the Navy's evaluation of its ocean engineering capability in regard to

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*Ocean engineering in this context includes the technologies required to support the development, design, and operation of systems for application in ocean depths greater than 100 meters in providing or performing: rescue, object search, location, identification and investigation; aircraft and object recovery; object/material inspection, disposal destruction or neutralization; deployment, precise placement, and recovery of underwater systems; construction, maintenance, repair and protection of permanent and semipermanent underwater installation; and salvage.

state of the art (knowledge and practice), forecasts of industrial development, and proposed thrusts (development) to be considered by the Navy in its research planning.

The panel was formed in January 1982 and structured in membership to include experts who have engaged in some aspects of each technical area covered in the Navy's report. The panel also is balanced with persons having experience in industry sponsored development and those engaged in university-based research. Panel members are engaged in engineering research and development within the oceans in such fields as acoustics, offshore construction, survey systems, hydrodynamics; others are responsible for undersea system program management of development including vehicles, life support, propulsion, and energy sources. Industrial research, on a broad technology basis, is part of the expertise provided by several members who have been responsible for R&D planning for major U.S. firms in highly diverse manufacturing and service operations as well as in research supporting ocean resource exploration, development, and production. Assessment of foreign activity was provided by using the information available to members involved in industrial development.

The panel used a review and assessment process based on working groups assigned to assess five categories of the fifteen technologies addressed in the Navy report (Table 2). Each working group was led by a panel member, and the group held one or more meetings to provide preliminary comments and background on the Navy evaluation; the six working group meetings and the participants are listed in Appendix A. This review provided the basis for the assessment undertaken at a workshop held September 23-24, 1982, in Washington, D.C., at the National Academy of Sciences.

The panel met, as a whole, on three occasions: in January 1982 to plan the details of the assessment approach, in June 1982 to receive a briefing on the Navy's mission concepts, and following the workshop to review the preliminary results of its technology assessment. These proceedings are the results, in commentary form, of the working group reviews and the assessments produced at the workshop.

The comments in the proceedings are those of the invited participants, as well as the panel members; no panel conclusions or overall recommendations are offered. Workshop participants were chosen by the panel based on the expertise needed in the each of the technical assessment categories and as a result of preworkshop reviews which indicated specific technical areas considered by the panel to be more critical to Navy research planning.

The organization of the proceedings follows the categorization of the 15 technologies evaluated by the Navy. These technologies initially were reviewed in five groups; the technologies were assessed later during the workshop in four sets, two of the working groups having been combined. The arrangement of technology assessments in these proceedings and the working group relationships are shown in Table 2. The format for each technology follows that used by the Navy in its evaluation; the Navy's statement is shown in standard print while **the commentary of the proceedings follows in bold print.**

The "energy systems" group of technologies is presented first since these technical activities result, to a major extent, in systems hardware which the other technologies must be able to support. The major cross-technology relationships between the energy group technologies and the others is discussed. Groups directly supporting the systems hardware are the "materials and testing" technologies, which are discussed next. "Data systems" and "control" are linked and are presented next in the series of assessment commentaries. The last grouping, "dynamics," assesses those analyses essential to a system's design and reliable performance. Clearly, aspects of other technology concerns, such as those involving materials and structures and nondestructive testing, must be taken into account in engineering analyses since they influence the character, extent, and capability to perform engineering analyses discussed in the "dynamics" group.

In the organization of the assessment process, it was necessary to force many artificial groupings to analyze the very broad technical base supporting Navy deep ocean activities. One of the functions of the workshop was to identify the major cross-technology relationships, and provision was made for experts in the affected working groups to interact with each other in framing an assessment which accounts for links between technologies.

These proceedings are organized according to the five working group areas; the fifteen technology assessments were assigned to each group topically. Workshop assessment formats for each technology follow the arrangement used in the Navy's earlier evaluation; namely: scope, objective, related technologies, state of the art, forecast, and proposed thrusts. Each of the 15 assessment sections begins with a U.S. Navy report excerpt and is followed by a the working group discussion. Many of the 15 assessments contain references which are listed at the end of the assessment section. An extensive bibliography on load handling is presented as Appendix C.

This review and assessment involved the participation of 56 panel members and experts during working group meetings as well as in the workshop itself. In addition, 34 Navy scientists and program management personnel assisted in the preparation for and at the workshop. The expertise and time provided by all participants were essential for this extensive effort, and are much appreciated by the panel, the Marine Board, and the National Research Council.

All material presented in these proceedings is unclassified. With the exception of one panel meeting in which Navy operational concepts were presented (June 25, 1982, at the Naval Ocean Systems Center), working group reviews, panel deliberations, and the workshop were conducted on a unclassified basis.

Appendix B is a statement reflecting the concerns of one working group participant, Dr. Alfred Bove*, and of Dr. Christian Lambertsen*, who was asked to comment on the preworkshop reviews of the energy system and life support working groups. These comments do not follow the format used in the working group assessments, nor were they reviewed and discussed on the same basis as were other technical comments. Nevertheless, Dr. Bove and Dr. Lambertsen have provided their independent assessment and addressed a technical issue worthy of consideration by the Navy in its research planning.

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*Dr. Alfred Bove is with the Cardiovascular Division, Mayo Clinic, Rochester, Minnesota. Dr. Christian Lambertsen is director of the Institute for Environmental Medicine, University of Pennsylvania, Philadephia.

TABLE 2 Working Group Assignments

Working Group	Technologies
Energy Systems (James Wenzel, leader)	o Energy Storage and Conversion o Life Support o Propulsion and Auxiliary Machinery
Materials and Testing (H. Ray Brannon, was leader during reviews; John Coltman was leader for the workshop)	o Materials and Structures o Nondestructive Testing o Geotechnics
Data Systems (R. Frank Busby, leader)	o Sensors o Data Transmission and Handling o Cables o Robotics, Teleoperators, and Work Systems
Control (Ira Dyer, leader)	o Command and Control o Navigation
Dynamics (Marshall Tulin, leader during reviews; Eugene Miller acted as coordinator during the workshop)	o Dynamic Response Prediction o Load Handling o Moorings

ENERGY SYSTEMS GROUP

Three technology areas -- energy storage and conversion, life support, and propulsion and auxiliary machinery -- are discussed in the following section under the energy systems group. These technologies -- along with robotics, teleoperators, and work systems, which are discussed later as part of the data systems group -- comprise the major hardware systems elements for deep ocean operations. There are many interrelationships between the energy systems technologies and those covered later in these proceedings; these cross-links are noted at the end of each of the technology assessments provided by the energy systems working group.

ENERGY STORAGE AND CONVERSION

U.S. Navy Report Excerpt

Scope

A. Generation
   1. Chemical
   2. Mechanical
   3. Nuclear
   4. Environmental

B. Conditioning

C. Storage

D. Distribution

Objective

Develop more effective and efficient generation, distribution, conditioning, and energy storage for unique ocean engineering applications.

<u>Working Group Review/Workshop Comments</u> The working group commented on further actions needed to assess research in this area; these comments are included in the introduction to these proceedings.

Related Technologies

Related technologies are: materials and structures; life support; nondestructive testing; and robotics, teleoperators, and work systems.

<u>Working Group Review/Workshop Comments</u> Workshop comments regarding interaction of energy storage and conversion with other technologies are found on page 29 in this section.

DISCUSSION OF ENERGY AND STORAGE CONVERSION

State of the Art

U.S. Navy Report

No single power source will meet all the power level and endurance requirements of undersea tasks; typically 10 to 1,000 kilowatts with endurance from 1 to 30 days. A variety of power sources are needed. Future systems will require energy provided by ship- or shore-generated electrical energy transmitted by cable, chemical energy systems (i.e., batteries, fuel cells, and thermal energy conversion systems) replenished by support ships, and nuclear reactors or radioisotope power systems which require only occasional maintenance and refueling.

Batteries generally are applicable to low endurance levels, and low endurance high-power requirements are associated with thermal energy conversion systems. Fuel cells are better suited for low to medium power levels requiring an endurance of more than 10 hours. Vehicles and underwater machinery will incorporate refuelable or rechargeable chemical energy plants or nuclear systems because electric cables impose serious handling and entanglement hazards. A fixed station moored at midocean depths or on the ocean bottom will require large amounts of energy. When the location is relatively near the shore, the energy can be generated best on shore and transmitted through cables. For remote locations, a self-contained energy system will be required. Divers usually will be able to obtain electrical energy through umbilical cables, but free swimmers working appreciable distances from base will need reliable, high capacity, portable energy packages.

Systems needing a self-contained energy source have used lead acid and silver zinc batteries. The lead acid battery is used because of its low cost, established reliability, and adaptability to submerged operation. The silver zinc battery is being used where higher energy availability per pound is needed. A fuel cell, which unlike the battery can produced energy as long as fuel and oxidant are provided, has been developed as a prototype and has been demonstrated on a submersible vehicle. This hydrogen oxygen fuel cell can provide several times the power density of a silver zinc battery although the operational costs are very high.

Thermodynamic power systems (operating on the Rankine, Brayton, or Sterling cycles and using a reciprocating engine or a turbine driving an electrical generator) could produce electrical energy at much less cost and weight than a nuclear system but have had little development until recently. For deep missions, it would be necessary to condense or recycle the exhaust and store it aboard, and maintain neutral buoyancy. A semiclosed-cycle diesel engine operating on stored oxygen and fuel oil has been demonstrated for shallow-depth requirements.

Working Group Review/Workshop Comments

The power level and duration quoted as 10 to 1,000 kilowatts for 1 to 30 days is perhaps too restrictive. It is suggested that realistic goals are power levels as low as a few hundred watts and duration of up to several months. Considering energy storge and conversion technologies, these can be split logically into the following categories:

- Batteries primary (not electrically rechargeable);
- Batteries secondary (electrically rechargeable);
- Fuel cells;
- Closed cycle engines;
- Open-cycle engines;
- Radioactive isotopes.

Batteries Primary Lithium aqueous electrolyte batteries should not be confused with lithium thionyl chloride ($LiSOCl_2$) and lithium sulfur dioxide ($LiSO_2$). The latter two systems present safety hazards after discharge.[1-7] Also these systems are already being developed extensively by industry for applications better suiting their chemistries; i.e., low capacity*, fairly low power rating. Therefore, it is not necessary for the Navy to participate in such development.

Significant work on the safety of primary batteries is an ongoing program at the Navy Surface Weapons Center (NSWC), and a NAVSEA Instruction 9310.1A of March 11, 1982, has been issued on safety and procedures for lithium batteries. The U.S. Air Force (USAF) is using a major $LiSOCl_2$ system in Minuteman silos; documentation on performance and safety should be available. Lithium aqueous systems do not represent a safety hazard before activation or after total discharge; the technology potentially can satisfy demands for high-power and high-energy density for durations of minutes to hours. Their safety during discharge remains an issue to be addressed. Some work has been done on pressure-compensated lithium-aqueous solutions. These systems have not so far been developed to a level of usefulness to the Navy.

*One exception is the $LiSOCl_2$ battery being developed by GTE for the Air Force as a Minuteman Survivable Power System.

<u>Batteries Secondary</u> In addition to lead acid and silver zinc batteries, which are considered state-of-practice secondaries for Navy applications, the working group suggests that state of the art nickel hydrogen (NiH_2) and silver hydrogen (AgH_2) batteries should also be considered for their exceptional life-cycle performance.[8-13] These systems can be adapted from USAF, NASA, and COMSAT applications -- 50 ampere-hour NiH_2 batteries are state of the art, at least in terms of low depths of discharge.* Greater capacity will require additional work.

<u>Fuel Cells</u> In contrast to the assessment that fuel cell operating cost is high, there is evidence that the cost is lower than that of silver zinc. In reality, the cost must be tied to mission needs. If the overall mission cost is taken into consideration, then the maximization of bottom time would far outweigh the oxygen, hydrogen, and other costs associated with operating fuel cells. The fact is that with the successful fuel cell demonstrations on Deep Quest and in space, fuel cells for deep ocean applications have become a viable state-of-the-art technology.[13-15]

<u>Closed-Cycle Engines</u> These systems require an external heat source which may be provided by various means: combustion reaction, stored heat, nuclear reaction, or radioactive isotopes. Some European development of the Sterling engine has been reported for submarine applications. A 20-kilowatt pressurized combustion system has been developed in Sweden by KB United Stirling A.B. and delivered for installation in a submersible suited for operations down to 300 meters (1,000 feet).

<u>Open-Cycle Engines</u> In an undersea operation, any open-cycle engine requires that an artificial atmosphere be created, and the disposal of the exhaust products is a difficult problem. Very little work has been reported on such systems for underwater use. Some patents have been awarded to European concerns for configuration of open-cycle engines designed to operate under water.[16, 17]

<u>Radioisotope Systems</u> Also for very long durations, radioisotope systems may be useful and need to be considered.

Finally, the Navy assessment should address power conditioning and distribution equipment.

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*Refer to Air Force Contract No. F33615-75-C-2059, Eagle - Picher Industries, Incorporated, Joplin, Missouri, 64801.

Forecast

U.S. Navy Report

Power source developments cover a very wide range. Technology advances specifically in higher energy couples have been driven primarily by automotive, space, and medical applications. These developments are potential candidates for underwater service, but each requires considerable adaptation to the ocean environment and to specific underwater applications. Clearly, no single candidate is preferable over the entire energy spectrum in which vehicles and other undersea systems may operate.

The diversity of advantages and disadvantages of each also accentuates the need for pursuing different approaches in power source development. Lead acid batteries with 20 percent greater energy density are expected. Nickel cadmium and nickel iron batteries are also under development for submarine use. Lithium thionyl chloride primary batteries are also under development to verify safety characteristics. A variety of other high energy couples are being developed by the Department of Energy. Fuel cell development for submersibles is nil; limited development is continuing in France. A lithium-fueled, closed-Rankine cycle engine (Stored Chemical Energy Propulsion System, SCEPS) is being developed for the advanced lightweight torpedo.

Working Group Review/Workshop Comments

Extensive fuel cell developments at United Technologies for the space and domestic sectors can only enhance the usefulness and economical prospects of these systems for special Navy needs. The Navy has already accomplished considerable development in the fuel cell for the Deep Quest program. The West German Navy continues to work on fuel cells for submarines. Siemens and General Electric (GE) are engaged in a cooperative program to develop practical modules, storing hydrogen as metal hydride and oxygen cryogenically. The technology uses the GE proprietary solid polymer electrolyte. Considerable work at GE on high temperature fuel cells may provide valuable technology. In the long term, a safe rechargeable lithium battery may emerge and previous work on lithium hydrogen peroxide and lithium silver oxide may be applicable to future systems. R&D on high temperature lithium metal sulfide systems is being sponsored by USAF for satellite applications. The lower-weight nickel zinc battery has significant potential submersible application, if the problem of zinc electrode unreliability can be solved. Both the Army and the Navy are sponsoring work on this problem. However, less important is the light weight of a battery. The anode weight is only a small fraction of the total battery; besides, for deep ocean use, a lighter-than-water battery would require ballasting.

The short reference to thermal engines in the forecast section probably underestimates the developments in this field in the next 20 years. In this period, it is likely that there will be more developments than the SCEPS. Perry is adapting a standard Wankel engine as an underwater power source in a closed-cycle system using scrubbers. Other systems based on the Rankine, Sterling, and perhaps Brayton cycles will probably be developed in Europe for submarine and submersible applications. These developments will not be generally available to the U.S. Navy except perhaps on an exchange basis. In addition, the work on diesel engines for shallow underwater applications (less than 200 meters) is likely to continue, and other internal combustion engines such as spark ignition and, eventually, high efficiency gas turbine engines will utilize these developments. Again, the developments are probably to be made in Europe, and perhaps Japan, but they may become available commercially.

Digital controls, based on the continued development of the microprocessor, are likely to improve the operation and control of all types of thermal power plants for underwater applications. The complex control sequence required to start up and operate these systems will be much easier and more reliable with digital control.

Proposed Thrusts

U.S. Navy Report

Development efforts should be directed to adapting emerging power source developments to systems specifically designed for the ocean environment. The following are first priority thrusts:

- The high-rate primary and secondary lithium batteries, specifically the lithium thionyl chloride battery for pressure-compensated ocean engineering applications, should be developed.

- The power density of deep-ocean fuel cells should be increased by the develoment of lightweight, pressure-compensated reactant storage and conversion subsystems.

- The power conditioning, control, protection, and regulation equipment needed for systems using high levels of electric power provided by cable should be developed.

- The Stored Chemical Energy Propulsion System for submersible vehicle applications, including the conversion of shaft power to electrical power, should be developed.

Working Group Review/Workshop Comments

Lithium thionyl chloride battery development should receive attention. At a minimum, the Navy should follow progress in industrial and government laboratories. This system will continue to be developed by the private sector for applications most suited to its chemistry. Also lithium aqueous primary batteries, which are inherently pressure-compensated, could be well suited to certain deep ocean technology needs. However, the anomalous behavior of lithium in aqueous solution needs to be addressed.

In terms of thermal power plants, there is a significant underestimation of what could and should be developed by the Navy for underwater applications. At a minimum, the systems that could enable any closed-cycle power plant to be utilized as an underwater power source should be investigated. Such systems would include energy storage, use of energy as the heat source for the engine, heat transfer, ocean interface, and the control system. Such systems could be integrated with little modification to Rankine, Sterling, and Brayton engines.

In addition, methods of converting open-cycle power plants for underwater operation should be developed. These developments, including silencing, would have application to other types of open-cycle engines, including diesel, spark ignition, and gas turbine engines.

The proposed thrust also would benefit by separating the dynamic system machinery from the heat sources and looking at a broad range of heat sources (e.g., molten salts).

It is desirable to consider integration of the energy storage system into the vehicle design as a whole by considering ways to incorporate the storage system components as actual structural members. The resulting reduction in total system weight and volume might significantly influence the choice of specific energy storage/propulsion candidates; e.g., fuel cells or batteries. The technology of pressure-compensated batteries is not fully understood. Improvements in this area could result in major improvements in system performance by the elimination of special purpose pressure vessels. Cell failure management, using modern diagnostic and data-handling systems, has the promise of extending useful cycle life and depth of discharge of electromechanical systems.

Interaction of Energy Storage and Conversion with Other Technologies

Technology areas that have direct interaction with energy storage and conversion development are identified as follows:

Dynamic Response Prediction Vehicle dynamics establish the mechanical loads and environmental conditions, such as attitudes, vibration levels, and rates of pressure change, which are required for the design of equipment discussed in the energy storage and conversion systems section.

Data Transmission and Handling Acoustic telemetry systems provide a means for remote control of power systems for unmanned submersibles (fuel cells or closed-cycle thermal devices). Fiber optics permit wide-band communication for command, control, and diagnostics of power system performance.

Robotics Robotics can simplify underwater replenishment of fuel cell power systems and the handling of hazardous materials associated with system components discussed in the energy storage and conversion technology area.

Sensors A "thrust" should be added to the discussion of sensors in regard to the need for process sensors for pressure, temperature, current voltage, fluid flow, and inventory of energy storage and conversion systems. The development of sensors for direct interface with fiber optics and digital data systems should be considered.

Cables Energy storage and conversion systems require relatively short power and instrumentation cables with many interconnects and penetrators. The development of fiber optics instrumentation cables could reduce requirements for penetration of the hull structure.

Command and Control Command and control technology is applicable directly to Energy storage and conversion systems in the areas of system start-up and shutdown, display and monitoring of performance, and digital programming of thermal systems.

Life Support The extension of life support capability in duration and numbers of crew will place greater demands on energy storage and conversion systems; at present, life support capacity limits useful submerged time. Waste heat from power conversion systems could be used in diver support systems.[12, 13] Careful attention should be paid to electrical isolation of the energy conversion system from the life support system hardware.

Materials and Structures Encapsulation of energy storage and conversion systems requires high-strength pressure vessels. Electrochemical systems generate, evolve, or utilize hydrogen, leading to possible embrittlement of materials. Welds and heat-affected zones must be considered and fracture mechanics design criteria must be observed.

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LIFE SUPPORT

U.S. Navy Report Excerpt

Scope

A. Physiology
   1. Decompression
   2. Standards
   3. Pharmacology

B. Atmospheric Conditioning
   1. Oxygen control
   2. Carbon dioxide control
   3. Thermal Control
   4. Contamination

C. Environmental Protection
   1. Thermal
   2. Electroshock
   3. Contaminants

D. Support Technology
   1. Gas generation and storage
   2. Hyperbaric facilities and components
   3. Umbilicals
   4. Sensors

Objective

Exploit new and emerging technologies to develop equipment which will improve the diver's safety and work efficiency throughout the water column.

Working Group Review/Workshop Comments To limit the complexity of the life support system requirements, the Long-Range Deep Ocean Technology Plan is limited to submersible/diver type systems. Operations with large numbers of people, such as nuclear submarine type systems, are not included. It is the Navy's primary objective to develop the personnel transfer capsule (PTC), and diver life support systems free from tethered umbilicals down to 600 meters in the ocean under hyperbaric conditions.

The 600-meter operating ocean depth is established by considering continental shelves, submersible bulkhead design, and physiological limitations. The working group recommends that the Navy should investigate long-term, one-atmosphere conditions with attention to the physiological effects of regenerative life support systems.

The areas requiring study and development to support the Navy life support systems are:

- o Atmospheric and breathing gas mixtures;
- o Compression and decompression techniques;
- o Oxygen supply and control;
- o Carbon dioxide monitor and control;
- o Environmental hazards monitor and control;
- o Temperature and humidity control;
- o Hotel facilities;
- o Life support related technology:
  - Command and control
  - Human factors
  - Energy storage and conversion
  - Emergency rescue
  - Sensors/materials.

Unless the commercial diving industries are convinced that the untethered PTC and free swimmer will enhance operation with increased safety, they will continue to use the tethered systems. The initial development of the umbilical free life support systems down to 600 meters in the ocean will have to be fully supported by the Navy. Industry has no requirement presently to develop equipment for this objective.

Related Technologies

Related technologies are: materials and structures; energy storage and conversion; nondestructive testing; sensors; and cables.

<u>Working Group Review/Workshop Comments</u> See comments regarding interaction of life support with other technologies at the end of this section.

DISCUSSION OF LIFE SUPPORT

State of the Art

U.S. Navy Report

Most Navy diving is conducted using scuba or surface-supported equipment with either air or nitrogen/oxygen gas mixtures. Useful work accomplished is limited by time, depth, and the need to follow complex and restricted decompression procedures. Deep helium/oxygen diving is conducted by divers tethered to diving bells and decompressed in a deck chamber at a rate of less than 30 meters sea water equivalent (100 fsw) per day.

Navy diving equipment was developed before specified physiologic requirements for life support apparatus were formulated. These systems were tested subjectively and offer inconsistent and perhaps inadequate performance.

Little is known about the effects of drugs at depth. Consequently, drugs and more exotic breathing mixtures such as nitrogen, oxygen and helium (trimix) are avoided. This provides an ultimate limitation to diving depth and speed of compression.

Except for open circuit apparatus, diving systems use a chemical carbon dioxide (CO_2)scrubber to remove CO_2 exhaled by divers and electromechanical oxygen injection systems to control the oxygen partial pressure in the chamber. Factors affecting scrubber efficiency are many, and it is therefore difficult to optimize design. Oxygen injection systems use an electrochemical cell to detect oxygen level. Shelf life of this cell is limited.

Precise temperature control is critical to diver safety. Open circuit, hot water-driven, heat exchangers warm both the diver's breathing gas and the CO_2 scrubber. Unless the CO_2 scrubber is heated, scrubbing efficiency and duration decreases radically. No controlling system to maintain temperature within prescribed limits is in use.

Criteria for permissible contaminant levels in diver breathing air and a means for their analysis have been defined. No criterion for helium/oxygen purity, especially for saturation diving, nor a system for contaminant measurement has yet been defined.

Several potential diver-carried heat sources are under investigation. Because of potential electrical shock and the lack of underwater electrical shock criteria, electrical heating is not under investigation.

Air diving is supported either by low-pressure compressors whi pump the air directly to the diver or high-pressure compressors whi store air in high pressure cylinders for later use. Helium/oxygen mixtures are prepared by mixing helium and oxygen from high pressur cylinders and storing the mixture as a gas in a high-pressure cylir

Life support systems used in personnel transfer capsules (PTCs deck decompression chambers (DDCs), or habitats tend to be large ar inefficient. Noisy blowers are used to circulate chamber atmospher through chemical bed CO_2 absorbents. Comparatively large amounts c power are required to maintain poorly insulated chambers at comfort temperatures. Humidity levels are comparatively high. The life sι port functions of oxygen control and carbon dioxide scrubbing for tethered divers are handled by a push-pull system which circulates chamber atmosphere through umbilicals and back to the chamber.

The tethered diver's umbilical consists of four components; a breathing gas hose, hot water supply hose, an instrumentation and communications cable, and a lifeline. These off-the-shelf hoses ar heavy (6.8 to 9 kilograms negative) and bulky (about 7.6 centimeter in diameter) and severely limit diver mobility. Lengths range from to 107 meters depending on use.

Working Group Review/Workshop Comments

The hyperbaric individual diver's life support systems present in operation by the Navy are: MK11, MK12, MK14 and MK15. PTCs and ASR (auxiliary submarine rescue) surface support ships team togethe to support the diver operations. The MK diver support systems are either open circuit, semiclosed circuit, or closed circuit in desig They may be used down to 300 meters in ocean depth. The PTCs are tethered from the surface support platform, which also carries the required decompression facilities on board.

Manned submersibles in active use by the Navy are: Sea Cliff, Turtle and the Deep Submergence Rescue Vehicle (DSRV). The underse vehicles are designed for 1-atmosphere pressure operation and opera down to 1,800 meters in depth. Sea Cliff is being modified to desc to 6,000 meters.

The life support systems operated by industries for divers and submersibles are similar in design to the Navy systems. The life support components which may be considered in an assessment of the state of the art are listed below:

- **Atmospheric mixing -- helium/oxygen, hydrogen/oxygen (European countries);**
- **Decompression techniques -- decompression procedure;**

- Oxygen supply and control -- high pressure gaseous, liquid nitrogen, potassium oxide (KO_2) chemical, polarographic sensor/amplifier, paramagnetic analyzer;
- Carbon dioxide monitor and control -- PH sensor/amplifier, infrared analyzer, LiOH, baralyme, sodasorb;
- Contaminants monitoring and control -- gas chromatograph, catalytic burner, activated charcoal;
- Temperature and humidity control -- hot water, electrical refrigeration, magnesium chip, thermoelectric;
- Diver suit -- total redesign for free swimmer;
- Hotel facilities -- food, water, waste, cloth, bedding (not discussed);
- Related technology -- (not discussed);
- Hyperbaric medicine and physiology.

Forecast

U.S. Navy Report

The commercial diving industry will continue to improve their push-pull diving systems and chamber systems. However, the industry does not appear to be greatly concerned with providing free swimming capability to their underwater workers. Work sites are stationary and needs are met adequately with umbilical-type diving systems. Efficient and smaller heat sources are of little concern since thermal protection can be adequately handled with hot water suits.

Increased Navy emphasis on smaller, more reliable control systems for self-contained breathing apparatus will cause applications of digital technology and advancement in CO_2 scrubbing. Advances in technology have provided a basis for improvement in submersible habitat life support systems. Electrochemical atmospheric conditioning systems capable of generating O_2 while scrubbing CO_2 should be applied.

Advances in plastics and related areas provided alternatives for the piping and storage of diving gases. Materials development leading to smaller, more flexible umbilicals will allow tethered divers to operate more efficiently in higher water currents. Umbilical connectors will be developed to provide more reliability in both gas and electrical connections.

Biomedical research will develop more efficient decompression techniques, reducing the time required for decompression and reducing the probability of divers being stricken with the bends. A more complete set of physiological standards and design criteria for breathing gas systems, thermal support systems, and visual and aural sensory enhancement systems will be developed to allow the design of optimized diver life support systems. A more thorough knowledge of the effects, dosages, and adverse reactions produced by the various drugs in the hyperbaric environment will be developed to combat undesirable reactions to the environment and to extend the scope of clinical care during long exposures.

Working Group Review/Workshop Comments

The state-of-the-art life support systems are used for either the one atmospheric environment or an umbilical-supported hyperbaric environment down to 300 meters. To achieve the primary objective, (a tether-free life support system down to 600 meters) all the state-of-the-art technology should be examined and new technology developed.

Atmospheric Mixing Under greater ocean depth, the feasibility of using helium and oxygen mix should be evaluated. The use of hydrogen/oxygen mix and trimix (helium/nitrogen/oxygen) may be more advantageous. If electrolysis of water is used, hydrogen/oxygen mix will be more attactive.

Decompression Technique The decompression schedule down to 600 meters must be established. Computer technology and hyperbaric pharmacology should be studied to enhance decompression operations.

Oxygen and Supply and Control The KO_2 life support system will supply oxygen and, at the same time, remove CO_2. One chemical performs the two essential functions of the manned systems, resulting in system simplicity and eliminating the stringent requirements of cleaning, material control, and handling associated with a high-pressure oxygen system. The proper operation of the KO_2 system has been demonstrated under a 1-atmosphere condition. Its operation under hyperbaric conditions should be evaluated.

The polarographic sensor/amplifier control equipment has been operated down to an ocean depth of 300 meters. Its operation down to 600 meters should be evaluated. The reliability and response time of the existing oxygen control equipment need to be improved to support the tethered, free life support systems. The Navy's and industries' requirements on the high-pressure oxygen systems, especially material selection, should be reviewed. It will be beneficial if the requirements of both are compatible.

Carbon Dioxide Monitoring and Control Similar comments as the oxygen supply and control system. Carbon dioxide allowable levels under hyperbaric conditions should be realistically defined, especially when the operation is for short duration, such as required with a free swimmer.

Environmental Hazard Monitoring and Control Contaminants allowable levels should be established. Monitoring and control equipment need to be developed.

Temperature and Humidity Control These should be studied; the power and size of control systems will be very critical for the free swimmer applications.

Hotel Facilities When the mission duration increases, the hotel facilities will be more critical. Under long mission duration, the portable PTC may be considered as habitat.

Proposed Thrusts

U.S. Navy Report

Biomedical Research Decompression procedures that allow for flexibility and maximum efficiency over the present restrictive tables, yet provide adequate protection from bends, should be developed. This, however, cannot be accomplished until an adequate model based upon expanded knowledge of the physiology of gas tranport is developed, verified, and carefully tested. Such a model might, for example, be incorporated in a decompression computer which provides the shortest yet most adequate decompression required and optimized for each diver. Under certain circumstances, improvements in efficiency of two- to three-fold are possible. Physiological standards for life support criteria need to be developed to allow design of more efficient life support systems. Hyperbaric pharmacology advances are needed to reduce the harmful effects of the environment and to extend the scope of clinical care during long exposure.

Atmospheric Conditioning Small and efficient systems that monitor the proper functioning of diving equipment should be developed. Small, portable sensors to monitor and control oxygen and CO_2 levels in both diving apparatus and chambers can be developed using current technology. This will result in a reduction in size and bulk of diving apparatus. Garment technology and portable heat sources should be pursued to determine the feasibility of developing variable insulation garments with wider usage in diving. Better gas purity criteria need to be developed, particularly where long-term exposure is required. Electrochemical atmospheric conditioning systems that generate O_2 while eliminating CO_2 should be developed for submersibles, habitats, and PTCs.

Environmental Protection The Navy Bureau of Medicine's effort to establish underwater electroshock criteria should be intensified. In deriving auxiliary heat, one of the most efficient available energy sources is based upon electrothermal conversion, but this cannot be addressed before electroshock limits are defined.

In consonance with the variable insulation garment, an effort should be initiated to develop outer garment materials that form a barrier to protect the diver from contamination (e.g, chemical and biological) as well as provide a water barrier for thermal protection.

Support Technology Methods of breathing, gas storage, and generation should be reexamined. Cryogenic storage should be investigated. Composite cylinders have been in use in applications other than diving; this approach should be investigated for high-pressure storage. Gas storage schemes such as chemical storge in metal hydrates, or in molecular sieves should be evaluated. In the generation of oxygen for breathing gas systems, it is possible to reduce high-pressure storage requirements by using a combination of lithium hydroxide and potassium superoxide in CO_2 scrubbing. Oxygen is a byproduct of the reaction and can be regulated by controlled sequencing of the chemicals. This approach warrants a feasibility investigation.

Working Group Review/Workshop Comments

With industries' and institutes' support, Navy has been conducting the following studies and development work in support of the tethered, free life support system applications:

- **PTCs and swimmer suit conceptual design;**
- **Oxygen and CO_2 control and monitoring techniques;**
- **Thermal insulation for temperature control to minimize power requirements; and**
- **Potassium oxide life support system -- theoretical analysis and performance evaluation under hyperbaric conditions.**

There is agreement with the Navy proposed thrusts in decompression study, physiological standards, contaminants and electroshock criteria. However, the Navy thrust should include "establishing a physiological basis for the elimination of inert gas in decompression and the study of physiological effects during compressions." These studies will be foundations for life support system development.

As the operations of PTCs and submersibles go deeper, some rescue method should be developed in case of emergency such as connecting an external life support package to extend the stay time while waiting to be rescued.

The Navy should be aware that all these thrusts will require basic biomedical research for their accomplishment.

Interaction of Life Support with other Technologies Technology areas, which are discussed more fully in other sections, that have direct interaction with life support development are identified as follows:

Load Handling Consider the problems of launch and recovery of an untethered personnel transfer capsule (PTC).

Data Transmission and Handling Consider an in-helmet data display for the diver; also communications and data transmission without using cables.

Sensors Life support systems require sensors to measure the internal and external environment.

Navigation The untethered diver must locate a distant worksite and return to the PTC or a base for decompression. The navigation system should have a 16 kilometer (10-mile) area navigation capability with rough accuracy and a terminal 90 meter (approximately 100-yard) navigation system with an accuracy of 0.3 meters (one foot) (to locate the entrance to the base).

Energy Storage Systems Life support will require electrical power and heat supply for the untethered PTC and diver.

Propulsion Propulsion will be required to give mobility to the untethered PTC and diver.

Materials Diving suit fabrics must meet requirements for thermal and hazardous environmental barriers. In selecting materials for life support systems in general, the off-gasing of toxic substances should be of constant concern.

PROPULSION AND AUXILIARY MACHINERY

U.S. Navy Report Excerpt

Scope

A. Electrical
B. Hydraulic
C. Pneumatic
D. Mechanical
E. Propulsion

Objective

Develop components and engineering data for specifying and/or designing improved external machinery systems and equipment for ocean engineering applications.

<u>Working Group Review/Workshop Comments</u> **The Navy Long-Range Deep Ocean Technology report is considered an accurate, though extremely general, summary in propulsion and auxiliary machinery areas. The way to accomplish mission tasks frequently involve the use of elements in combinations for which they were not originally intended. In addition, an extremely pertinent set of constraints, which are part of the overall system solution to a problem, is the set imposed by the support systems including, for example, the surface vessel. The overall scheme to transmit power to a bottom operating vehicle is dependent on the system characteristics of the power supply available from the surface ship.**

In the original DSRV design, many of the drivers in the design were introduced by aircraft limitations and support ship contraints in handling through the air/sea interface. The Navy personnel were fully cognizant of this facet of system design, however, within the scope of Deep Ocean Technology (DOT), they focused somewhat on the technical problems occurring below 100 meters.

Although the Navy may be fully cognizant of the system design implications, it is important to recognize that the definition of DOT as the regime below 100 meters can mask systems problems relating to the interaction with the interface at the surface and result in development hazards. Equal priority must be given to the systems and technology aspects of launch, recovery, and surface support, when optimizing vehicle concepts for deep underwater operations.

Related Technologies

Related technologies are: cables; and materials and structures.

Working Group Review/Workshop Comments In addition to other technologies suggested, refer to comments at the end of the section on interaction with other technologies.

DISCUSSION OF PROPULSION AND AUXILIARY SYSTEMS

State of the Art

U.S. Navy Report

Machinery and electrical equipment have been developed for operation in the atmosphere or in the vacuum of space, but the ocean's high pressure and corrosiveness impose more severe demands than have been encountered in most previous applications. Military submarines operate with most machinery systems inside the pressure hull and a minimum of equipment exposed to the ocean environment. In deep submersibles it is desirable to use as little heavy-pressure resistant structure as possible. Consequently, efficient design requires the use of equipment located outside the primary hull and exposed directly to the ocean environment. Advanced systems will be required to be more compact, lighter, quieter, and more efficient.

A key element of mobile undersea systems is propulsion. Propulsion machinery consists of electric drive systems or hydraulic drives which are driven by electric motors. Hydraulic motors are used to drive pumps or speed reducers. Electric power conversion or conditioning is required, and generally a motor speed controller is also needed. The electric input power is, in most cases, provided by a direct current (dc) source via a power distribution system consisting of cabling, penetrators, power sensors, and switching devices. Development has focused on discovering and resolving failure modes and understanding interaction of off-the-shelf equipment which has been modified to operate in seawater or in an oil-filled container. Considerable engineering data has been developed for improving the reliability of new designs to power levels of 25 horsepower.

Most state-of-the-art systems consist of modified equipment designed for other purposes and are inefficient and heavy. These systems are one-of-a-kind designs and expensive. Pressure tolerant electonics has had only limited demonstration outside the laboratory. High-power electrical hull penetrators are large and very expensive. Advanced hydraulic control components have low tolerance for seawater leakage.

A seawater hydraulic motor has been developed for prototype evaluation in diver's tools. Ballast systems have been developed for both pumped and gas generator displacement systems. High pressure seawater pumping systems for 7.6 liters per minute have been developed. Lubricants which can tolerate seawater leakage have improved the reliability of power transmission components.

Working Group Review/Workshop Comments

The state-of-the-art assessment is considered accurate. The Lockheed Missiles and Space Company's ocean mining program, however, has used 1,000-horsepower alternating current electric motors, well above the 25 horsepower motors mentioned in the Navy text. It should be noted that the Navy report does not differentiate between ac and dc motor technology, nor between weight-sensitive swimming vehicles and weight-insensitive bottom crawlers. German companies, such as KSB (Klein, Shanzlin and Becker), have special purpose motor designs in the high horsepower range available for offshore applications. In a compact package, the Navy felt a need existed at about 100 horsepower. The report does not address a number of components already developed and deployed in the DSRV program such as pressure-compensated oil-filled (PCOF) cables, fiber optics cables, solid state circuit breakers, and quiet motor controllers.

Forecast

U.S. Navy Report

Advancement is dependent on Navy support since the commercial market is generally limited to offshore drilling depths, and the commitment of industrial R&D is not justified by profit or volume. Future systems will be dependent on adaptation of available designs which are modified according to experience and data developed in the laboratory. Industrial progress in electric power control and conditioning will increase efficiency and reliability of higher power systems although this equipment may require adaptation to using a dc input. Seawater hydraulics will be developed for diver's tools.

Working Group Review/Workshop Comments

The Navy report appears accurate, though brief. The dominant interest of the offshore oil community is in improved reliability for equipment operating in about 300 meters, with possible extension to 900 meters in particular cases. If the existing inventory of equipment does not fit Navy missions, Navy-sponsored development will be required. Developments in deep ocean mining and in the National Science Foundation's sponsored scientific drilling program (using research ships, Glomar Challenger and the Explorer, which may be converted to a drill ship) should be monitored as potential improvements, but should not be relied on to meet specific Navy needs. The use of seawater hydraulics need not be confined to the particular application mentioned (i.e., diver's tools) but will involve care in selection of materials.

Proposed Thrusts

U.S. Navy Report

More efficient, reliable, quieter, and lighter weight external subsystems are critical to deeper ocean operating capability. This includes propulsion, hydraulics, electrical distribution, and buoyancy control systems.

The following thrusts include the application of several emerging technologies: advances in power electronics, microprocessors, and the use of acoustic data and control links. Propulsion system power and reliability must be improved for higher powered tethered systems. Submersible electric transformers, motor controllers, and motors having power to 100 horsepower and 4,000-volt ac input require development. The reliability of this equipment must be increased to permit uninterrupted operations for one-week periods. Equipment must be developed to detect, evaluate, and correct equipment faults automatically. Electrical insulation capable of withstanding high voltage and a seawater pressure environment must be improved. Failure analysis techniques are required to reduce maintenance turn-around time and cost.

Acoustically quiet machinery, specifically hydraulic systems and gearing, is required for some operations and to minimize interference with acoustic systems. Noise attenuation and devices need developing for operating in the high-pressure seawater environment.

Reliable and smaller multiconductor electrical hull penetrators are essential to systems development.

More efficient, compact, and reliable electric drives and power distribution systems are required for mobile systems having self-contained power supplies. Application of micropressors will increase efficiency and improve reliability and compactness of the distribution system. Automatic control of machinery and performance monitoring is required.

Efficient buoyancy generation techniques and systems must be developed to improve the resultant net buoyancy per pound at deep depths.

Working Group Review/Workshop Comments

The assessment appears accurate. Acoustic issues deserve particular attention, including attention to the basic physical mechanisms of noise generation and transmission into the ocean. More attention should be paid to the machinery required by bottom-crawling

vehicles and other work systems. The admitted difficulty of developing pressure-tolerant electronics should not discourage the pursuit of this technology for special applications, particularly in such areas as external sensor installations.

<u>Interaction with Other Technologies</u> Interacting technologies include: energy and storage conversion systems; robotics, teleoperators, and work systems; and materials and structures. (These technologies are discussed later, with particular attention to materials compatibility in fluid-compensated systems for higher voltage applications.) Hydraulic and electric motor technology will be available to meet requirements imposed by manipulators and other robotic systems.

MATERIALS AND TESTING GROUP

Of the three technologies addressed by this working group on materials and testing and discussed in this section, two technologies are closely related -- materials and structures and nondestructive testing (NDT). The requirements for and performance of the materials must meet the criteria and judgment of adequacy provided by the testing processes. The third technology, geotechnics, is related to the other two; the character of the seafloor provides one element of the design requirements for undersea structures and may influence the need for new approaches and techniques in applying NDT.

MATERIALS AND STRUCTURES

U.S. Navy Report Excerpt

Scope

A. Structural
   1. Pressure resistant
      a. metallic
      b. nonmetallic
   2. Joining
   3. Flexible
      a. wire ropes
      b. synthetic lines
   4. Rigid
      a. foundations
      b. exostructure

B. Nonstructural
   1. Compensating fluids
   2. Seals
   3. Lubricants
   4. Hydraulic fluids
   5. Buoyancy materials
      a. gases
      b. solids
   6. Dielectrics
   7. Anechoics
   8. Antifoulants

Objective

Improve the efficiency and safety of ocean engineering systems through the development and characterization of materials and structures.

Related Technologies

Related technologies are: system dynamic response prediction; data transmission and handling; moorings; load handling; robotics, teleoperators, and work systems; energy storage and conversion; life support; nondestructive testing; propulsion and auxiliary machinery; geotechnics; and cables.

DISCUSSION OF MATERIALS AND STRUCTURES

State of the Art

U.S. Navy Report

Structural materials for applications such as pressure hulls, exostructures, and solid flotation typically are expensive, heavy, easily degraded in the environment, and often unavailable for timel procurement. Weight and strength (specific strength or weight/displacement ratio) are particularly important for structures that must be handled at sea because of significant impacts on the size o support platforms and related equipment. Pressure hulls can be fabricated from a variety of metals including high-strength steels, aluminum, and titanium. By use of the latter, a man-rated hull for 4,000-meter depths has been produced with a weight/displacement rat of 0.7. For lesser depths, fiber-reinforced plastic, reinforced concrete, acrylic, and glass have been demonstrated but not sufficiently characterized for optimum designs.

A variety of materials has been used in cable fabrication. Although metallic strength elements are well developed for use in d submergence applications, they exhibit such undesirable features as high weight, corrosion, and large bend radius. Synthetics such as nylon, Kevlar, and polyester often overcome these limitations with much higher strength/weight ratios and are used routinely for tensi load applications up to 450,000 kilograms. Unfortunately, the beha of synthetic cable materials and cable structures is not well understood.

Buoyancy from gas generators or syntactic foam can be used to 6,000 meters. Decomposition of liquid hydrazine at 6,000 meters is currently achievable but with relatively low efficiency (approximat 3.3 displacement/weight factor). Syntactic foam for use at 6,000-meter depths is now routinely produced with a specific gravity of 0.

Nonstructural materials such as hydraulic and pressure compensating fluids, dielectrics, corrosion inhibitors, and seals, used routinely in many applications but require frequent attention are generally intolerant of seawater intrusion.

Effective acoustic baffling for sonar transducers has been demonstrated to full ocean depths. However, anechoic material to reduce machinery-generated noise has been limited to depths less th 100 meters. Likewise, materials for thermal insulation have only b effective at very shallow depths.

Nondestructive testing (NDT) methods exist for most materials prior to their inclusion in a system or their use at sea. In situ NDT however, is rudimentary. Consequently, the actual condition of many materials, particularly synthetics, is unknown during use.

Working Group Review/Workshop Comments

The Navy report is silent on the state of the art in several areas related to materials and structures that the working group considers to be important. These areas include: fabrication and joining, repair, characterization of material properties and expected performance, capability to specify design criteria needed to achieve specified performance, design procedures and capability, and environmentally sensitive mechanical behavior. The Navy has proposed thrusts in several of these areas.

Satisfactory NDT methods do not exist for many classes of materials even prior to their inclusion in a system or use at sea.

There is little industrial work aimed at improving deep-depth syntactic foams.

Forecast

U.S. Navy Report

Materials development will continue on fundamental levels at academic and other research institutions with little regard for requirements of the ocean environment. Ocean engineering applications will be addressed primarily by the offshore oil industry, limited to specific requirements and profit margin. Historically, this industry has relied on, rather than contributed to, government materials development.

Within the government, development will continue for large-scale applications such as habitats, submarines, arrays, and weapons. These areas often represent complementary efforts which may be modified and applied to ocean engineering systems. Materials development for specific ocean engineering applications is unlikely without Navy support. For example, improved buoyancy materials or pressure hulls for great depths are not normally required by communities outside deep submergence. Additionally, even though there is widespread use of some materials, such as synthetic lines, significant improvements for ocean engineering are unlikely to be made through commercial development.

Working Group Review/Workshop Comments

In some cases, new materials developed by industry or academia (as well as by the Navy) will be useful to deep ocean technology. Materials research and development that is ocean-environment related is going on at such institutions as the University of Delaware, Lewes, Delaware, 19958; and at Florida Atlantic University, Boca Raton, Florida, 33431. Even so, design and fabrication of Navy structures and further characterization under Navy use conditions will remain the responsibility of the Navy.

Many of the improvements in materials for ocean engineering will clearly require Navy initiative, as forecasted. For example, commercial developments are not likely to address needs related to 6,000-meter pressure hulls and buoyancy. In contrast to the Navy forecast, however, it appears likely that significant improvements in synthetic lines will grow out of widespread commercial use and attendant product improvement.

The structures and materials section covers a very great breadth of technology (more than 20 areas of thrusts are identified in the Navy report). Significant advances will require careful focus of efforts on high-priority needs, accompanied by the earlist possible identification of end-use developments.

In the absence of comment on design and analysis capability, the Navy should ensure that such capability be addressed some place in the overall plan. For example, the analysis of thick composite structures with multi-axial states of stress is not covered.

Proposed Thrusts

U.S. Navy Report

A significant exploratory development effort should be directed toward more efficient pressure-resistant structures. Weight/displacement ratios of 0.5 for 6,000-meter depths will be necessary for future systems and can be achieved using fiber composites or ceramics. To accomplish this, however, extensive data is required on failure mechanisms, design criteria, testing (including nondestructive), and manufacturing processes, including joining techniques. As an adjunct, transparent materials, such as acrylics and glass, need to be reexamined as both pressure hull and viewpoint possibilities. Concurrent efforts should be accelerated to develop large-scale titanium pressure housings, with particular emphasis on welding processes. Low-cost materials such as concrete should be improved for bottom-fixed housings or hyperbaric test installations.

Working Group Review/Workshop Comments

Considerations should be particularly given to recent advances in concrete technology.[1, 2] Dramatic advances are being made in developing high strength concretes, largely through the addition of micro silicate particles (silica fumes) and steel fibers, so that strength-weight ratios for structures loaded primarily in compression are now approaching those of steel. Prestressing techniques make it practicable to construct hyperbaric test chambers up to 68,900 pascals (10,000 psi) internal pressure which are essentially fatigue free and more economical than steel. Such a chamber has been constructed in the United Kingdom.

The possibility of using advanced high-strength metallic materials to construct deep submergence vehicles should continue to be considered.

U.S. Navy Report

Effort should be directed toward establishing the material properties and use factors which lead to degradation of synthetic lines, such as nylon and Kevlar. This would include the effects of ultraviolet and seawater exposure, age, and fatigue. Dielectric materials for power/signal insulation should be researched to reduce electromechanical cable sizes. Strain insulation materials must be developed to improve the mechanical properties of fiber optic cables.

Working Group Review/Workshop Comments

There are current programs on cables and lines[3, 4] in industry and in the OCIMF (Oil Company's International Materials Forum), but Navy efforts as described are desirable in the opinion of the working group.

U.S. Navy Report

Lighter weight buoyancy materials and systems should be developed with a specific gravity of 0.4 for 6,000-meter depths as a realistic goal. This will require new constituent components and improved performance evaluation techniques. A corollary thrust ought to be the use of foam as a structural material; the foam could be augmented by fiber inclusion or other means and then evaluated in terms of its ability to be shaped in various structural configurations. Gas generation systems with high hydrogen yield should be pursued to full ocean depths. Hydrolysis of lithium hydride is one potential candidate which should be explored.

Advantage should be taken of the properties of evolving fiber composite and sandwich materials. The aerospace industry has done extensive work in this area that can be effectively exploited for a variety of ocean engineering applications, including exostructures and piping.

Considerable effort should be directed toward improving materials and processes related to ocean engineering machinery (tribology). This effort should center around increased reliability, longer service, and environmental compatibility.

Working Group Review/Workshop Comments

The problems of ocean engineering machinery are accelerated at great depths because of the high pressures encountered and the extension of intrusion of sea water. The thrusts in this area should be directed toward design and materials improvement to reduce distortion and the associated operational problems.

U.S. Navy Report

Anechoic materials should be developed for in-water equipment which can provide up to 20-decibel shielding over a wide frequency spectrum to depths of 6,000 meters. Wear and corrosion-resistant materials should be improved to make such things as seawater hydraulics a practical reality. Simple seals and bearings, such as solid fiber-impregnated synthetics, should be qualified for long life (at least twice what is now possible) and high reliability under both high- and low-pressure applications.

The areas of welding, bonding, and repair patching require additional investment. The basic materials and processes of welding need to be addressed in the light of environmental exposure. Fabrication of thick-walled structures, in particular, require automated, high quality-controlled techniques for welding. Underwater techniques, particularly at greater depths, should be improved to permit in situ welds by submersibles which will approach the quality of those now achievable on land. Pyrotechnic methods may be able to satisfy this goal and should be developed further. Bonding and adhesive materials, long used by the aerospace industry, should be increasingly adapted to the ocean environment to simplify joining processes and reduce weight of undersea systems. Effective in situ patching and repair techniques should be pushed to minimize requirements for recovery/replacement/implantment of ocean engineering structures.

In a related field, the Electric Power Research Institute has sponsored, for several years, a program for explosive bonding of heat exchanger tubes to tube sheets. Immediate applications are to land-based nuclear power plants; the original impetus came from the ocean thermal energy conversion program.[5, 6]

Working Group Review/Workshop Comments

It is likely that oil and other offshore industries will improve welding, bonding, and patching techniques for underwater use. Improvements from these areas will have application to Navy needs through the range of water depths of commercial operations. The Navy's needs, however, extend to greater depths than are expected in the near term for commercial operations.

Needed are continued development of NDT, particularly for nonmetallic materials and for materials in structures, and the ability to predict service performance from NDT data. Design of structures to facilitate NDT is desirable.

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3. Deterioration of Synthetic Fiber Rope During Marine Usage. Sea Grant Office, MIT, Cambridge, Massachusetts 02139. Principal investigators: Stanley Backer, Frederick J. McGarry, and James H. Williams, Jr.

4. Hawser Task Force. Oil Company International Marine Forum (OCIMF), London Headquarters, (Contact: John F. Flory, P. E., Civil & Marine Engineering Division, Exxon Production Research and Engineering Company, P.O. Box 101, Florham Park, New Jersey 07932.) (Objective: Establish quality-control standards by which rope performance can be assured.)

NONDESTRUCTIVE TESTING

U.S. Navy Report Excerpt

Scope

A. Acoustic
   1. Ultrasonic
   2. Resonant vibration

B. Electromagnetic
   1. Optical
   2. Magnetic

C. Radiographic
   1. Tomography
   2. X-Ray
   3. Gamma ray

D. Other
   1. Mechanical
   2. Penetrant dye
   3. Electronic

Objective

Develop the capability to perform in situ nondestructive test and evaluation of underwater equipment, structures, and facilities.

<u>Working Group Review/Workshop Comments</u> The scope of the Navy's needs in this area include inspection, evaluation, and monitoring for incipient failure as well as the more narrow conventional NDT techniques. The distinction is not always clear in the text.

Related Technologies

Related technologies are: data transmission and handling; load handling; materials and structures; energy storage and conversion; sensors; moorings (inspection), life support, navigation; and, robotics, teleoperators, and work systems.

DISCUSSION OF NONDESTRUCTIVE TESTING

Optimal use of failure-model based structural design methodologies (i.e., fracture mechanics) calls for nondestructive measurement techniques to be developed in determining the type, size, shape, and orientation of defects to make rational accept or reject decisions. Considerable progress in developing quantitative techniques has been made over the last decade in the aerospace and nuclear industry.

State of the Art

U.S. Navy Report

Underwater inspection is largely limited to visual observations. Hidden deterioration cannot be identified until it is revealed by an abnormal surface condition or by structural failure. Development of underwater nondestructive test and evaluation (NDT&E) thus far has concentrated on improved techniques and equipment for use by diver-inspectors. The emphasis has been on methods for nondestructive inspection of steel, concrete, or timber structural elements of waterfront structures and inspection of steel hulls of ships. The methods investigated have included low- and high-frequency ultrasonics, other acoustic techniques, axial tomography, magnetic particle inspections, and stereophotographic documentation of surface defects.

Working Group Review/Workshop Comments

Research is underway on evaluating the potential of vibrational analysis techniques and acoustic emission techniques for in situ continuous monitoring of undersea structures.*

Inspection robots, used extensively within the nuclear power industry, can provide a technology base which may be useful in remote inspection techniques.

U.S. Navy Report

Ultrasonic methods using pulse-echo and direct transmission techniques have been used to inspect wooden pilings and steel structures under water. For use on metallic elements, conventional ultrasonic methods suffer from excessive scattering due to corrosion

*Refer to Dr. Nicholas Perrone, Office of Naval Research.

pits on the front surface of the object being inspected. A recent preliminary evaluation of nonconventional (i.e., Lamb wave, focused transducer) ultrasonic technologies to inspect corroded underwater structures has shown that methods using focused transducers with acoustic apertures and digital signal processing show considerable promise.

Development of electrical and electromagnetic NDT&E methods has been hindered by concerns for electrical safety for the divers. The techniques that have been investigated include eddy current, magnetic induction, and magnetic particle. These techniques have found limited application, particularly in inspection of welds and joints for flaws. They have not been used for thickness measurement of corroded materials. Recent development of a fast response ground fault protection system may allow wider development of electromagnetic techniques.

The feasibility of computed axial tomography for underwater NDT&E has been demonstrated in laboratory experiments. Application of this powerful technique to in situ inspection will require substantial hardware development.

Mechanical methods for underwater NDT&E include rebound (i.e., Schmidt hammer) and impulse-response techniques. The former is useful for determining surface conditions, while the latter can provide an assessment of overall structural integrity. However, neither has been used in deep water.

Little has been done to date in addressing the inspection of coatings on underwater structures other than visual observation of blisters and peeling. The introduction of new coating materials which may be applied in situ makes it desirable to develop techniques to detect damage to these coatings at an early stage when they can be repaired before extensive damage of the base material occurs.

Working Group Review/Workshop Comments

Surface fouling appears to be a limiting factor in underwater inspection. Consideration should be given to an R&D thrust related to in situ surface cleaning and preparation for NDT&E.* Photo-laser acoustic techniques to characterize the nature of surface fouling are under development.**

***Refer to the Department of the Interior, Minerals Management Service, John B. Gregory.**

****Refer to the University of Delaware, College of Marine Studies, Lewes, Delaware, 19958, Dr. S. C. Dexter; <u>Photo Acoustic Spectroscopy for the Study of Biofilm Formation Underwater</u>, September 1982, final report to the Office of Naval Research.**

There is no difference between the Navy and commercial requirements for nondestructive testing and evaluation over the range of water depths in which both organizations operate. Accordingly, it seems likely that a high degree of interchange of technology would occur for these water depths. One major area that strongly distinguishes the Navy's needs from other users is testing of deep submergence vehicles.

Forecast

U.S. Navy Report

In the absence of a specific, directed program of advanced development by the Navy, it is unlikely that the commercial sector will develop underwater NDT&E equipment and techniques appropriate to Navy requirements, since the potential market is small and highly specialized. Radiographic, magnetic particle, and ultrasonic inspection methods for offshore structures will continue to be developed for the oil industry. Some of this technology and equipment will be adaptable to Navy use. Engineering studies of an underwater computerized axial tomography inspection system will continue under Navy contract. Other techniques may be developed (e.g., eddy current, impulse response) for the offshore industry. The generally turbid waters and cramped nature of sites of Navy inspection interest will encourage development of acoustic inspection systems with a high degree of automation. The larger number of Navy sites requiring inspection will encourage application of sophisticated data processing and analysis techniques; these are not likely to be developed commercially because of the limited market.

Working Group Review/Workshop Comments

Rapid developments are expected over the next 20 years by industry in microelectronics and robotics, which will provide major new opportunities for automating the total inspection procedure.

Major generic technical advances are anticipated in the next 20 years that will provide the ability to use acoustic and electromagnetic techniques for the nondestructive measurement of defects. Passive techniques such as vibrational analysis and acoustic emission will probably require direct Navy support if they are to be developed sufficiently for Navy use.

Considerable developments in robotics and remote-operated vehicle (ROV) technology is anticipated, independent of NDT&E. Technology from this will likely be applicable to remote inspection techniques.

Proposed Thrusts

U.S. Navy Report

Recent developments in several technology areas have reduced the cost and time required to conduct underwater NDT&E. In turn, this will allow substantial reductions in the manpower and training required for underwater inspections especially for the diver-inspector. This results from developments in each of the activities in the inspection process: the underwater inspection itself, data acquisition and processing, and data evaluation and analysis. The proposed thrusts address improvements in each of these areas.

Acoustic Imaging Two emerging acoustic imaging technologies show particular promise for application to, in situ inspection of underwater equipment, facilities, and structures. Both of these approaches take advantage of the acoustic transmission characteristics of the seawater medium. An acoustic television system is under development for navigation and obstacle avoidance use on small submersibles. This system has demonstrated a remarkable capability to detect relatively small objects under conditions of zero visibility. The image resolution required for underwater inspection, is however, considerably greater than the present system. Improvement can probably be accomplished by use of different transduction techniques in the imaging device (e.g., charge-coupled devices) and by application of image enhancement methods (discussed later).

An alternative method is acoustic holography which uses acoustic phase information to construct three-dimensional images. Systems using this principle have been applied to medical diagnostics. Again, application to underwater NDT&E requires significant improvement in image resolution.

It should be noted that the data generated by either of these techniques is particularly suitable for digital processing. An alternative to the techniques just discussed is an enhanced-image sidescan sonar, which may have particular application to rapid, if somewhat coarse, evaluation (e.g., in wartime). Here, also, the data provided by the inspection device can be processed digitally.

Working Group Review/Workshop Comments

Acoustic imaging should more properly be referred to as acoustic vision, and the objective of this effort explicitly stated as the development of techniques for replacing the current visual inspection performed by divers.

U.S. Navy Report

Data Processing The advent of powerful but field-portable miniprocessors has created the opportunity for rapid on-site acquisition and processing of underwater NDT&E data. Presently, nearly all data are processed visually by an operator. The data are usually in the form of numbers (e.g., transmit times for ultrasonic pulses) or strip charts (e.g., ultrasonic pulse wave forms). The availability of data in a digital-compatible form (as from the systems described previously) will allow the processing of the data on-site.

A thrust should address this aspect of the NDT&E process. Emphasis should be placed on means for enhancing the images produced by the inwater inspection equipment. Enormous progress has been made in recent years in image enhancement. Remarkably clear images can be produced from relatively low quality data. The implications for underwater NDT&E are substantial. Inspections can be made more rapidly, with less resolution but higher data rates. Processing of the data topside to enhance the images will substantially improve inspection rates.

Pattern Recognition Once the data are in digital form, another powerful advance in processing can be applied. Application of pattern recognition to evaluation of inspection data should be investigated. By teaching a processor to search for specific patterns in the data (these would be visual clues to a human operator), large volumes of data can be reviewed and evaluated rapidly. The resultant information can be used to assess the condition of the structure, to alert operators to a requirement for more detailed inspection of specific areas, to compare present results with previous data, and to eliminate the collection of erroneous data.

Working Group Review/Workshop Comments

The thrusts on data processing and pattern recognition are far too general and should be directed toward specific NDT&E techniques; for example, acoustic vision, reflectometry, or model analysis. In like manner, the subjects of image recognition as such are too broad to be suitable as thrusts and should be replaced by NDT&E techniques development which includes the use of data processing and pattern recognition as appropriate for underwater use.

U.S. Navy Report

Remote Inspection With the development of computerized data acquisition, interpretation, and analysis, the requirement for an on-site, trained inspector can be almost entirely eliminated. At this point, it becomes feasible to consider development of a remote inspection system for use in hazardous areas or at depths greater than those accessible by divers. The major developments required for such a system are navigation and accurate position control in areas with limited access and, in some cases, large amounts of debris; surface cleaning and preparation; and sensor positioning and manipulation.

Working Group Review/Workshop Comments

Techniques to enhance inspection of large fixed structures by use of implanted internal sensors, which are monitored and interpreted remotely, should be considered.[1]

The NDT thrusts should be closely coupled with research in failure-model developments and the development of optimal accept or reject criteria to exploit this technology effectively.

REFERENCE

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GEOTECHNICS

U.S. Navy Report Excerpt

Scope

A. Seafloor property measurement
   1. Cohesionless soils
      a. calcareous soils
   2. Cohesive soils

B. Engineering behavior of calcareous soils
   1. Basic characteristics
   2. Response to loads

C. Analytics
   1. Soil/structure interaction
      a. cohesive soil
      b. cohesionless soil

D. Contour mapping
   1. Acoustic Holography

E. Seafloor modification
   1. Turbidity control
   2. Soil modification
   3. Slope stabilization
   4. Seafloor excavation

Objective

Develop techniques for measuring, evaluating, predicting, and modifying the engineering properties of the seafloor for ocean engineering operations.

Relat d Technologies

Related technologies are: cables; command and control; data transmission and handling; system dynamic response prediction; load handling; materials and structures; moorings; navigation; and sensors.

DISCUSSION OF GEOTECHNICS

State of the Art

U.S. Navy Report

Coring and laboratory tests plus dynamic penetrometers can provide good measurement or estimates of the properties of cohesive soils (i.e., clays). The properties of cohesionless soils are more difficult to measure. In moderate water depths (i.e., less than 300 meters), downhole core tests give good results but require drilled and cased holes which are expensive. In deep water (i.e., greater than 300 meters), cohesionless soil property determinations cannot be readily made; coring often fails to return a sample, and those samples recovered are highly disturbed.

Calcareous soil, a type of cohesionless material which covers approximately 45 percent of the world's seafloors, is particularly difficult to obtain data from because this material exhibits varying degrees of cementation and grain crushing. State of the art sampling devices (coring and grab devices) destroy the fabric of the material and thus render the sample useless for property determination.

Geotechnical analysis in the ocean is for the most part the same as on land, with notable exceptions being dynamic penetration, impact, and anchor-holding capacity. Predictive models and analytical techniques are available for pile capacity, bearing capacity, slope stability, earth pressure, and settlement for cohesive and most cohesionless soils; the exception being calcareous soils. Seafloor penetration analysis is limited to slender objects entering the soil with their major axis vertical. Analysis predicting shallow penetration and g-loading of impact events is not now generally possible. Anchor capacity prediction is limited to simple shapes; no general procedures are available for conventional anchors. Little recent attention has been directed at modifying the ocean floor to enhance its engineering characteristics or to mitigate locally adverse conditions such as high turbidity or slope instability. Navigation nets and depth sounders are coupled to plotters to generate contour maps in shallow to moderately deep water (i.e., 2,000 meters). Such maps can be highly valuable in assessing general seafloor characteristics.

Working Group Review/Workshop Comments

Undue emphasis appears to be given to soil property measurement by dynamic penetrometers. Many static in situ measurement techniques occupy a more prominent place in the state of the art, and their use is being extended rapidly into deeper water.[1, 2]

Downhole cone tests do not require cased holes.

Current industry capability for in situ testing is approximately 700 meters in water depth versus the 300 meters given in the Navy evaluation. Also, coring capabilities extend to about 300 meters below the seafloor in this water depth, and good quality samples of sands and clays (i.e., push samples) can be obtained. (Push sampling techniques are omitted in the Navy report.)

Sampling and in situ bore hole testing in near surface soils (i.e., top 20 feet) is generally most difficult and most subject to disturbance. Problems are aggravated in water depths greater than about 200 meters, and by very soft sediments.

The Navy report should recognize the increasing emphasis on geophysical (including high resolution subbottom profiling and side scan sonar) and geological data collection at deepwater sites to achieve a more comprehensive characterization of the site.[3]

Some capability does exist to predict quasi-static penetration of large objects into the seafloor, although prediction capabilities for impact events are poor, as pointed out by the Navy.

Widespread occurrence of silts in areas of interest to the Navy is expected, and improved capabilities to sample and to characterize properties and behavior of silts will be needed. The Navy identifies only calcareous materials as presenting an unusual material problem.

Mining industry studies regarding trafficability of earth moving equipment on the deep ocean floor are highly advanced, including the influence of engineering properties of the sediments.[4]

Forecast

U.S. Navy Report

As private industry moves into deeper water for nodule mining and oil recovery, geotechnical advances are likely to follow. Property measurement techniques for cohesive soils are expected to remain essentially the same except that measurements in deeper water may be possible, although these will be very time consuming and expensive to make. For cohesionless soils a similar trend is expected with little improvement in the quality of measurements.

The Navy will complete development of a 12-meter static cone penetrometer for shallow water (greater emphasis by the Navy and industry is being placed on static cone testing). Empirical correlations will be developed to allow cone data to be used directly for design. Some technical advancements are expected in analysis of calcareous soils where a better understanding of this material's response to loads is required.

Finite element models of geotechnical problems will be used to a greater degree than is done presently, but only on complex or large projects. Smaller projects will continue to rely on standard empirical design techniques. Methods to predict holding capacity of drag anchors will be developed. Little effort is expected in the area of seafloor modification unless the commercial sector finds that such modification produces construction/production cost savings. Contour mapping capablities will be extended into deep water, but little improvement in accuracy or map quality is expected.

Working Group Review/Workshop Comments

Geotechnical advances by industry in the form of sampling and in situ devices for use in deeper water are more certain than the Navy forecast suggests. Oil industry developments of a variety of such tools for water depths to 2,000 meters are underway; there is an active British program for development of such tools in 6,000 meters of water in connection with nuclear waste disposal.[5]

Existing correlations for using cone data directly for design should be recognized as well as the expected improvements. The report suggests that correlations remain to be developed.

With regard to calcareous soils, advancements are expected in sampling as well as in analysis.

Proposed Thrusts

U.S. Navy Report

Measurement of Cohesionless Soil Properties A major deficiency to be overcome is in the area of property measurement of deep ocean cohesionless soils. The 12-meter static cone penetrometer as presently configured will be of limited value in water depths greater than 100 meters due to its size, weight, and power requirements. For deepwater use, a second generation device will be required that does not need high weight to resist cone thrust, is small for ease of handling, and has its own onboard power, control, and data recording or telemetry systems. Rapid measurement systems based on acoustic methods should also be considered after a fuller understanding of the material has been developed.

Working Group Review/Workshop Comments

Although geophysical methods can be developed and improved which would significantly enhance site characterization, reservations are expressed concerning the general quantification of engineering properties from acoustic exploration methods. Efforts to develop such quantification will be attended by high risks although success would bring high rewards. Low emphasis by industry is expected.

For a long range program, the stated focus on developing a secondgeneration version of the 12-meter cone appears too limited. Consideration should be given to alternate remotely operated mechanical devices which penetrate and in some way measure engineering properties in the top 30 meters of seabed.

U.S. Navy Report

Rapid Measurement of Cohesive Soil Properties While the engineering behavior of cohesive soils is better understood than cohesionless soil, cohesive soil property measurement or sampling in the deep ocean remains a costly and time consuming task. A concerted effort should be undertaken to perfect underway continuous reading acoustic methods for large-scale geotechnical surveys backed up with low-cost expendable probes to validate the acoustic data and to provide the geotechnical details on the seafloor over a local area of interest.

Working Group Review/Workshop Comments

Exclusive attention to rapid (i.e., underway) measurement of cohesive soil properties appears too limited and inconsistent with the commitment to use tethered devices to investigate cohesionless soils.

Attention needs to be given to methods of quantifying silt and floc mixtures with specific gravity near 1.0. Such sites are characterized by gradually increased density and no distinct bottom. Optical, acoustic, and radioactive methods of measurement appear most promising to acquire data for modeling these materials.

U.S. Navy Report

Engineering Behavior of Calcareous Soils A concerted effort is required to develop a better understanding of engineering properties of calcareous soils. The response of this material to loads is highly variable and does not conform to accepted geotechnical theory for reasons which are not known but may be related to the soil's degree of cementation, grain crushability, crushed grain fraction, and carbonate content. The disparity between existing theory and the observed behavior of this material needs to be resolved through a combination of laboratory and at-sea tests. Once the behavior is understood, appropriate design procedures will then be developed and validated.

Working Group Review/Workshop Comments

A necessary step in understanding engineering properties of calcareous soils is improvement in characterization and classification of these materials. Development programs should include use of field tests to supplement laboratory and at-sea tests. Compared to industry, the Navy has a broader range of near-term problems and opportunities for development programs in existing operations worldwide. Thus, industry response to its specific problems may not extend to the more general needs of the Navy.

There is a need to develop an ability to characterize the properties of silts under various degrees of consolidation. This need is particularly related to arctic seabed construction planning.[6]

U.S. Navy Report

Improved Analytical Methods Improved methods for analyzing deep ocean soil/structure interaction problems need to be developed. For some problems, solutions have been developed for the terrestrial case and need only to be generalized to the marine soil case by the addition of parameters such as static or dynamic pore pressure. The finite element method has much potential in marine geotechnical engineering, however, significant work needs to be done to couple this method to the marine environment through properly formulated soil models. Semiempirical formulations for seafloor penetration and impact also are needed. In every case, the new analytical methods need to be validated either with existing data or with laboratory or field data from tests specifically designed to test the new analysis techniques.

Working Group Review/Workshop Comments

The thrust should be modified to de-emphasize extension of terrestrial methods and to focus on extension and generalization of existing methods to new deepwater problems.

Improvements sought should focus on foundation response and performance rather than simple stability.

Program design should recognize that meaningful improvements in prediction capability strongly depend on calibration by observation of prototype performance.

Testing of analytical models should be extended to include detailed comparisons of specific responses (e.g., pore pressure, stress) and not global response alone.

U.S. Navy Report

Contour Mapping A concerted effort needs to be undertaken to improve our ability to produce detailed contour maps of the seafloor. From a geotechnical viewpoint, the more that is known about the physical appearance of the seafloor, the more that can be inferred about its origin and its general engineering characteristics. Detailed contour maps of an area not only provide a strong indication of what soil type is likely to be found at a site, but they also would be extremely valuable in selecting specific sites for structures which would rest on or be attached to the seafloor. Acoustic holography has the potential to provide a detailed three-dimensional view of the ocean floor and should be developed to the point where it can be used to produce high quality contour maps.

Working Group Review/Workshop Comments

The emphasis on contour mapping should be expanded to include other types of high resolution geophysical mapping, including subbottom profiling.

U.S. Navy Report

Seafloor Modification A concerted effort should be undertaken to develop the equipment and methods needed to modify as necessary the seafloor's engineering properties or local topography. Seafloor work usually results in increased local turbidity and greatly reduced visibility. The means to control or remove turbidity by overlays, soil additives, or flushing should be developed.

Modification of the engineering properties of the seafloor, even if only for a a short time, could be highly valuable. Artificially induced soil liquefaction could be used to bury structural components such as anchors or footings. Injection of additives or chemicals into the soil to alter its strength characteristics; development of the capability to excavate, level, or otherwise prepare a site; and development of techniques to reduce extensive slope failures or turbidity flows could turn many operationally desirable sites, which are unsatisfactory from a geotechnical engineering point of view, into fully acceptable construction sites. While the risk of these developments for deep ocean use is high, the potential payoff in terms of increased site selections, flexibility, and simplified structural designs is also high.

Working Group Review/Workshop Comments

The prospects for successful modification of the engineering properties of seafloor soils are very poor. Such modifications in terrestrial construction are costly but, more important, are extremely limited to conditions that allow successful treatment. However, localized seafloor modification has been successfully practiced in several foreign countries. For example, in Japan, chemical improvement (lime stabilization) of underwater clays is used in harbor construction projects, such as at quay walls. Dynamic consolidation of granular materials has been carried out in Norway and France.

Attempts to develop techniques for improvement of slope stability over large areas are considered to be a high risk in terms of probable success. Emphasis on improving available techniques and skills for recognition and avoidance of unstable sites would probably be more effective.

Scope stability in moderate water depths (100 meters or less) is attainable through surcharge and drainage techniques and probably can be extended to greater depths. Drainage, to prevent liquefaction, has been incorporated recently at three platform sites at a depth of 160 meters, in the North Sea.

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DATA SYSTEMS GROUP

Four technologies are seen by the committee to be highly interrelated in their common functions of data gathering, processing, and transmission. These technologies are: sensors, data transmission and handling, cables, and robotics, teleoperators, and work systems. As noted earlier, robotics, teleoperators, and work systems are closely aligned to the energy systems technologies. The evolution and development of undersea sensing, data processing and interpretation, and related work systems cannot be considered separately from command and control and life support systems. In addition, the technologies discussed earlier under the topic of "life support" are associated with the human being as a sensor and decision maker and are, therefore, system are intimately related to data acquisition and control in research planning considerations.

SENSORS

U.S. Navy Report Excerpt

SCOPE

A. Acoustic
B. Optical
C. Electromagnetic
D. Thermal
E. Mechanical
F. Magnetic
G. Electric
H. Nuclear
I. Chemical

Objective

Develop, integrate, and validate improved sensory equipment and techniques for ocean applications.

Related Technologies

Related technologies are: data transmission and handling; moorings; load handling; robotics, teleoperators, and work systems; nondestructive testing; life support; command and control; navigation; and geotechnics.

Working Group Review/Workshop Comments A delineation and analysis of sensor requirements would be necessary to validate some of the Navy's statements with regard to inadequacy of oceanograhic sensors. In general, the Navy's outlook on sensor availability is unduly pessimistic.

DISCUSSION OF SENSORS

State of the Art

U.S. Navy Report

Today, the basic sensor is typically not the limiting factor in the detection of the desired stimulus. For example, very sensitive magnetometers are available but are limited by platform motion. Likewise, very sensitive hydrophones are available but are limited by ambient noise or flow noise.

Traditional imaging techniques, using both acoustic and electromagnetic (primarily light) sensors, are being investigated.

Oceanographic sensors for measuring waves, currents, and water properties are available in a variety of forms to meet the needs of the ocean science community. However, these devices frequently fail to produce data that can be used by engineers for design and monitoring purposes because of conflicts between ocean science and engineering data gathering philosophy and precision.

Working Group Review/Workshop Comments

Exception is taken to the Navy's statement that "[scientific instruments] frequently fail to produce data that can be used by engineers." The reliability and ruggedness of oceanographic instrumentation has been improved markedly over the past decade and extensive experience in making pertinent engineering and operational measurements has been accumulated in both the commercial and oceanographic sectors. In general, instruments required by the scientific community provide data of higher resolution and accuracy than most engineering requirements. The data output can be easily modified to meet less stringent needs.

Observations regarding the Navy's assessment of the state of the art are:

- **Due to the increasing efforts by the offshore oil industry, in situ oceanographic sensors previously used by the scientific community have been modified and made more rugged.**

- **Real-time data links have been developed. These data links include hard wire, acoustic, and satellite transmission. Typical systems include profiling current meters and (CTD)** telemetering linkups for relaying current and thermal data, acoustically telemetering moored sensors, and telemetering directional wave buoys. The microprocessor is being used to provide immediate data processing aboard operating platforms.

- o There is agreement with the Navy that the state of the art in basic sensor development of optical sensors is not a limiting factor. Optical sensors are approaching the photon level of sensitivity.

Forecast

U.S. Navy Report

Acoustics will remain the primary underwater sensing technique, with optical systems playing an important secondary role. No large-scale improvement is forecasted in sensor technology without a major fundamental breakthrough.

Near-term gains will continue to be accomplished by innovative implementation techniques of state-of-the-art components, information processing, and packaging of sensors.

Oceanographic sensor development to meet ocean science needs will concentrate on drifting devices, improved surface wind sensors, and ocean chemical and physical microstructure measuring apparatus. There also will be substantial improvements made in biological sensing techniques. Engineering sensors in the past have evolved from ocean science instrumentation, and this pattern is expected to continue.

Working Group Review/Workshop Comments

Exception is taken to the Navy's statement with respect to the improbability of large-scale improvement in sensor technologies without major fundamental breakthrough occurring. This key deviation from the Navy report is noted because of changes taking place in both acoustic and optical sensors. Present developments in polymer hydrophones, flexible piezoelectric materials, extended element sensors, and fiber optic sensors suggest that sensors technology will improve in a continuing and evolutionary manner.

Other observations are:

- o The statement of oceanographic sensors does not appear to be consistent with the overall objectives of the sensor section. References to drifting devices, improved surface wind sensors, and other components seem incomplete relative to ocean engineering data requirements. There will be a continuing need to obtain physical parameters at engineering sites or along data transmission paths, including acoustical, optical, and electromagnetic, and measurement of turbulence during transmission. Surface wind measurements become important in conjunction with satellite and other meteorological data for the prediction of weather windows for engineering projects.

- Work is underway by many ocean instrument manufacturers both in the United States and abroad to provide a widening array of instruments for both scientific and engineering purposes. Leadership in this area lies in the United States. Optical imaging instrumentation development involves intense foreign competition, particularly from Japan.

- It does not appear that the Navy's requirements will be significantly different than that of the offshore oil industry. No economic, proprietary, or market forces appear to be potential problems to the Navy's development program or to the acquisition of industrially developed instruments.

Proposed Thrusts

U.S. Navy Report

Imaging techniques Two scales of imaging techniques need to be developed; large-area (thousands of square meters) and small-area high resolution. Both acoustical and optical imaging techniques should be developed to improve ocean floor searches. A renewed effort should be made to develop the ability to image large areas of the seafloor by optical means. The water column, depending on its purity, can transmit optical information with a resolution of a few milliradians over distances of 50 to 100 meters. Areas of 5,000 to 10,000 square meters can be photographed if backscattered light from the illuminating source can be eliminated; 50 to 100 square meters is the limit now. Range gate techniques, with image-intensified cameras, can achieve this goal. The small-area high resolution imaging is necessary for diver and underwater work systems when operating in turbid waters.

Oceanographic sensors Improved wave measuring techniques are required, and ocean current and water property sensors are needed that have been specifically adapted to provide engineering design and performance information.

Acoustic Detection Advanced detection techniques should be developed by using the results of research from bionic pulse techniques (broadband signal), array signal processing, and artificial intelligence (e.g, pattern recognition, knowledge representation).

Working Group Review/Workshop Comments

There are two deviations from the Navy report as follows:

- Optical survey techniques can cover 2,000 to 3,000 square meters as developed during the period, 1966-1975, by NRL under the LIBEC program), not the 50 to 100 square meters cited.[1]

- Future diver physiological sensors will require diver readout and nonhardwire data links to either a submerged or surface monitoring station. The sensors will not only measure physiological parameters but also hazardous environmental parameters such as the presence of chemical and nuclear sources and electrical energy fields.

Observations regarding the sensor thrust include:

- The thrusts should address the definition of engineering requirements and sensory techniques necessary for the acquisition of sensors and the implementation of field programs to define water column characteristics for data transmission of acoustic, optical, and electro-magnetic information as well as to test sensors. Achieving this goal would enhance the Navy's ability to carry out remote ocean detection tasks.

- Considerable wave and current measuring equipment is available which could be adapted to Navy needs with a minimum effort.

- An effort to improve liaison between Navy engineers and scientists should be made to promote a better understanding of existing data sets and their acquisition. This effort would alleviate problems referenced in the Navy's state-of-the-art statement.

- The proposed Navy thrust labeled "acoustic detection" appears to be narrow in both viewpoint and area of application. There are major capability enhancement possibilities by adapting recent advances in hull-mounted and towed sonar systems to the deep ocean environment. Advanced techniques in sensors, integrated sensors/processing, and range gating are applicable to search and detection, imaging, inspection, and navigation (terrain recognition).

- Forward and side-looking imaging techniques will assist greatly in large-area coverage, particularly in relation to search missions. The oceanographic and academic communities are especially interested in this subject and will be pursuing large-area survey techniques for application to marine geology surveys.

DATA TRANSMISSION AND HANDLING

U.S. Navy Report Excerpt

Scope

A. Transmission
  1. Soft
    a. Acoustic
    b. Radio frequency
    c. Optical
    d. Electromagnetic
  2. Hard
    a. Fiber optic
    b. Conductivity

B. Handling
  1. Storage
  2. Retrieval
  3. Display

C. Processing
  1. Pattern recognition
  2. Correlation
  3. Integration

Objective

Develop techniques to improve data transfer between ocean platforms and to enhance decision making by use of advanced components, processing, and display.

Related Technologies

Related technologies are: sensors; command and control; materials and structures; robotics, teleoperators, and work system; moorings; nondestructive testing; geotechnics; and cables.

DISCUSSION OF DATA TRANSMISSION AND HANDLING

State of the Art

U.S. Navy Report

Transmission technology encompasses acoustic, optical, and even radio frequency (RF) links in the water column, and optical and RF links in hard cables. For the water column, acoustic linkage is the most common method, but it is subject to bandwidth limitations and multipath interference. Optical imaging is short range, whether it be photographic or real-time television transmitted over a hard link. Radio frequency transmission in the water has been tried for short-range secure data transfer near the seafloor. Very Low Frequency (VLF) is used in the Omega navigation system, usable a few meters below the surface, and audio frequency electromagnetic radiation is used for diver-to-diver communications. The use of Kevlar as a strength member has reduced the weight and size of electromechanical cables. Ocean cables containing optical fibers are becoming available; they are lighter, smaller, and have greater bandwidth capabilities than their electrical counterparts.

Digital data storage is based on the use of magnetic tape or disk for mass storage and solid-state elements for short-term storage. The photographic emulsion remains dominant for images, whether recorded immediately by a camera or presented for inspection on a television screen and then photographed. Underwater television cameras have been developed with charge-coupled device (CCD) image planes, which make them more sturdy and compact. Data display methods are conventional, with cathode ray tube (CRT) display used for data presentation in bulk and light-emitting diodes (LED) and gas plasma devices for individual characters.

Data processing is heavily dependent on microprocessors and the software developed for them. Typical tasks include simple pattern recognition; general signal processing which includes, for example, online Fast Fourier Transform routines for spectra analysis and error-correcting algorithms for data streams; and finally, both auto- and cross-correlation for analog signals to enhance signal-to-noise ratios.

Working Group Review/Workshop Comments

There are no major exceptions or deviations from the Navy report, however, there are several technical considerations that may influence research planning. These are presented as follows:

- o Acoustic linkage in the water column is subject to Doppler spreading, as well as to bandwidth limitations and multipath reverberation. Relevant developments in acoustic telemetry systems not included in the Navy's report are:

- o Acoustic telemetry systems have been developed in both the Navy and civilian sectors. Presently, civil development includes the command/control of well heads at 40 bits/sec operating over several kilometers using FSK (frequency shift keying). In addition, competitive systems exist in England, France, and Japan. NOSC has developed a deep ocean bottom-to-surface system that operates with coherent signaling at 4,800 bits/sec; however, it is sensitive to multipath interference. Several systems exist that operate at bit rates between these two rates. In addition, a French acoustical link for slow-scan Television has operated at 20,000 bits/sec over a kilometer.* Parametric sonars, which mitigate multi- path effects significantly but have high power requirements, have broadcasted both music and television over a few kilometers with high fidelity. In addition, there are several RF repeater systems for relaying data transmitted to the ocean surface to shore via satellite.

- o Optical imaging or communication also is limited severely by turbidity.

- o The comparative technical advantages of Kevlar versus steel are still unclear.

- o In the United States, most development efforts dealing with ocean cables containing optical elements have been supported with Navy funding. At the present time, there is an insufficient engineering data base on fiber optical cables. Issues concerning manufacture, wear, degradation, and penetrators need to be resolved before the full potential of their large bandwidths are realized for deep ocean applications.

- o Data storage and display have been, and will continue to be, heavily dependent upon advances by nonocean-related developments. These are affected by very competitive markets in both the United States and abroad, with Japan being a leader in some important facets of the technology.

*Comment refers to Thomson-CSF TSM 5555 "Through Water TV".

Forecast

U.S. Navy Report

Work in progress is evolutionary and derived from developments taking place in nonocean areas. Optical imaging at sea is beginning to exploit image-intensifier technology already developed for low-light-level viewing, and developments in optical fiber technology are resulting in lower attentuation in cables. Mass memories based on magnetic bubble storage are expected to enhance the capabilities of upcoming generations of microcomputers. More elaborate algorithms for pattern recognition, real-time estimation for controls, and target identification and discrimination are being developed.

Working Group Review/Workshop Comments

No major deviations from or modifications to the Navy report are noted. However, the following technical points are for the Navy's consideration of trends:

- Acoustic telemetry performance will probably improve by factors of 2 to 3 stimulated by industry's needs. High density energy sources may make parametric sonars attractive.

- Through-water optical communication links are intrinsically short range, however, their large bandwidths may make them useful for specific applications.

- Development in fiber optical cables must deal with problems such as cable degradation from shipboard use, high-strength penetrators, and water-tight connectors; these will be overcome but will require Navy support. (See section on cables).

- In the area of mass data storage, the course of development of magnetic bubble storage is uncertain. Semiconductor memories for intermediate data storage and laser disc storage for large data bases are important developments to follow.

- In situ processing will implement algorithms for pattern recognition. Commercial interest for specific underwater applications will be intense, particularly those concerned with offshore structures. The technology associated with high density energy sources, optical cables, and very large scale integrated-circuit (VLSIC) electronics will probably be proprietary but available to the Navy from U.S. suppliers.

Proposed Thrusts

U.S. Navy Report

Acoustic (Cable-Free) Data and Control Links Work should be undertaken to standardize underwater acoustic telemetry practice to accelerate development of a reliable acoustic data transfer system suitable for general use between ocean platforms. This could free small submersibles, for example, from tethers to their mother ships and greatly increase their operating speeds. The effects of multipath interference can be mitigated by more elaborate signal processing than has been used in the past and by the acceptance of certain operational restrictions.

Optical Signal Transmission Efforts should be initiated to develop a subsurface-surface optical communication link with water as the sole transmitting medium. Distances of 20 to 100 meters are feasible, depending on water quality. Development problems include the design and reliable operation of rapidly pulsed blue-green lasers and the application of image intensifier technology to receiving optics which must frequently operate in the presence of background illumination.

Display Display technology must be developed to maximize the efficiency of information transfer between a signal processing device and the human operator. For deep ocean applications, the use of stereo or three-dimensional presentation is likely to be of value, as is the use of color to provide an artificial perspective in certain nongeometric data arrays. Nonoptical "display" techniques should be also explored, such as the use of auditory patterns or even two-dimensional arrays of tactile excitation applied to the skin, similar to those techniques being explored to provide sensors for the blind. Finally, the relative merits of analog versus digital display for various kinds of information should be investigated and, if possible, quantified for use in future equipment design.

Working Group Review/Workshop Comments

The are no major deviations to the thrust objectives of the Navy report. However, standardization is not desirable for acoustic telemetry at this time since acoustic telemetry technology is still very much in a development stage. Attempts at standardization would probably impede progress. The following suggestions are made in research planning:

- **Extended capability in acoustic (cable free) data and control. Extension of the capabilities of underwater acoustic telemetry, especially as it applies to untethered vehicle command and control, should be considered.**

Trade-offs of range, data rate, and error rate acceptability should be made against the operational requirements of these vehicles. On-board data processing and semiautonomous control can minimize the communication requirements over the band-limited acoustic channel. Channel characterization for both deep and shallow operational scenarios should be determined. Particular emphasis should be given to the effects of mult-ipath and Doppler spreading. Models for both the self-noise of underwater vehicles and man-made noise in work areas need to be determined.

- Achievement of greater underwater bandwidths and higher data rates The use of relatively close-spaced underwater repeater stations for both acoustic and optical transmission is one approach to achieving tetherless transmission of data over long paths either to the surface or to bottom stations.

- Development of data compression techniques to maximize the use of limited capacity underwater communication channels The techniques will require sophisticated, compact, low-power data compression at the signal source. Systems for remote vehicles will draw upon the advances in microprocessors and mass memories but will require specially developed data compression algorithms.

REFERENCE

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CABLES

U.S. Navy Report Excerpt

Scope

A. Analysis
   1. Static
   2. Dynamic
   3. Fiber optics cables
   4. Umbilical cables (with life support)

B. Design
   1. Power and transmission cables
   2. Mechanical cables (synthetic and wire)

C. Connectors, penetrators, and terminations

D. Repair

Objective

Develop accurate analysis, design, and production techniques to obtain reliable undersea cable systems for communications, towed, and tethered applications.

Working Group Review/Workshop Comments The objective statement is vague. The objective should be to acquire a technology base from which it is possible to specify and predict the performance of a broad choice of both conventional and newly developed ropes and cable for marine communication for towed and tethered applications in terms of predictive models, choice of materials, designs, realistic test procedures, maintenance requirements, and accessories.

Questioned is the usefulness of that part of the Navy's objective related to the Navy's developing undersea cable production techniques.

Related Technologies

Related technologies are: materials and structures; data transmission and handling; moorings; load handling; life support; propulsion and auxiliary machinery; and geotechnics.

DISCUSSION OF CABLES

State of the Art

U.S. Navy Report

Present technology efforts center on the development of cables which have vastly improved data transmission capabilities and reduced size and weight characteristics through the use of fiber optics, synthetic load-bearing materials, and new hybrid materials. Underwater electromechanical and mooring cables are being built using synthetic strength members to improve their mechanical characteristics and reduce cable diameter and weight. The application of fiber optics to underwater cables has recently emerged. The major problems are the susceptibility of optical fibers to fatigue failure and attenuation due to bending. Analytical models have been developed to describe cable behavior but are far from being complete. A major deficiency is the lack of a thorough understanding of the behavior and interactions of cable components and materials, particularly synthetics, under various loading conditions. Also, there is no reliable method of analytically predicting fatigue failure in cables. Even test data exhibit so much scatter that cable failure often remains unpredictable. The exception is a retirement criteria for wire rope, developed after years of use. Computer models for analyzing cable dynamics under operational conditions have been developed. There appears to be a reasonable agreement with experimental data, but further verification is needed.

Connectors, penetrators, and terminations remain a major problem in terms of reliability and because the lack of cable standardization requires a new connector design for each new cable design. Fiber optic connectors and penetrators are in the development stage.

Only limited types of repairs can be performed on cables, and the performance of both electrical and mechanical components which have been repaired will always be less than that of new cable. The determination of repairability depends on the specific cable and the extent of damage. For the majority of damages, particularly those involving complex electromechanical or electro-optical-mechanical cables, repair is difficult if not impossible.

Working Group Review/Workshop Comments

There are no major deviations from the Navy's report. However, in the group's opinion, the state-of-the-art section does not emphasize sufficiently that while a great deal is known about basic mechanical cables, there is an inadequate data base with respect to predicting performance, retirement criteria, and repair. The need for better specifications is ever-present.

AD-A143 751 PROCEEDINGS OF A WORKSHOP ON NAVY LONG-RANGE DEEP OCEAN TECHNOLOGY: AN AS..(U) NATIONAL RESEARCH COUNCIL WASHINGTON DC MARINE BOARD I DYER 1983 2/2

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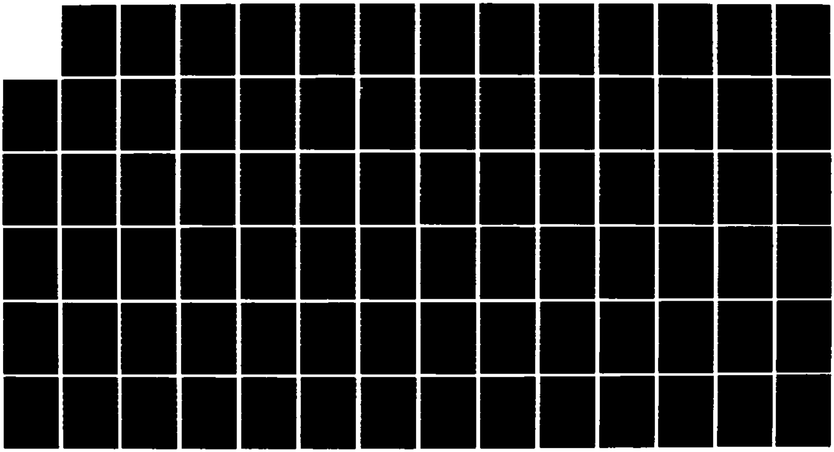

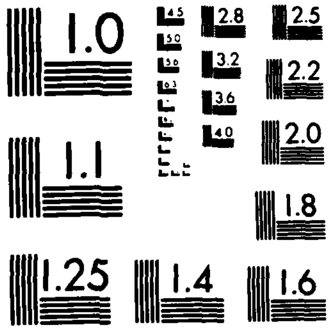

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Forecast

U.S. Navy Report

The Navy is collecting and synthesizing information on undersea cable technology and will publish a comprehensive guide for designing and analyzing cables as integral parts of systems. The information contained in this guide will not advance the state of the art in technology but will document the existing technology. Some of this technology has not yet been promulgated in the open literature.

The Navy has initiated an extensive program to investigate the characteristics of synthetic rope to resolve problems associated with its use. The goal is to develop inspection and retirement criteria for synthetic rope comparable to that established for wire rope.

Present efforts to develop reliable, transoceanic optical communication sytems, especially those which also carry electrical power, will be continued by both the Navy and industry. The Navy emphasis is on small diameter optical and electro-optical cables for deployment from aircraft and small ships. Industry is emphasizing large cables to fit the capabilities of existing manufacturing plants and cable-lying ships. The use of fiber optics in underwater cables will continue to increase as tolerance to dynamic flexure loading is improved.

New work in underwater electrical connectors and penetrators will consist of modifications to existing designs and special hardware. Laboratory experiments on underwater fiber optic penetrators and connectors have been started.

Unless the damage to a cable is simple, repair will continue to be complex, costly, or impractical. Repairs resulting in increased diameters at the repair site may be a problem if the cable must interact with a handling system.

Working Group Review/Workshop Comments

There are no major deviations from the Navy report. However, the following observations are made of concern to the Navy's forecast:

- **As industry develops new synthetic cable materials for Navy and the offshore industry use, a data base for the short-term and long-term performance will be required to make prudent selections among the available materials. Independent evaluation of the manufacturer's stated performance will be required to validate many potential applications of the evolving new materials. Standard or quasi-standard test procedures will be required.**

- The best analytical and design models for conventional cables are proprietary, belonging to the cable manufacturers, and these models will contiuue to be unavailable in the open literature.

- The use of fiber optic cables will increase significantly when the production problems become understood and solved, and when reliable specifications can be given which result in highly predictable transmission characteristics.

- Japan will continue to challenge the United States in its leadership in the development of underwater fiber optic cables.

Proposed Thrusts

U.S. Navy Report

Fiber Optics New materials technologies ought to be investigated that take full advantage of the separation allowed between power, telemetry, and strength functions in the cable to improve cable characteristics, performance, and reliability.

Working Group Review/Workshop Comments

A comprehensive systems engineering analysis and test of fiber optics in deep ocean technology applications, including environmental factors, shipboard handling equipments, and inspection, test and repair at sea may speed the transition of the use of fiber optics or at least bring to light associated problems and risks.

Optical investigation of single-mode and low loss nonsilica glasses of small diameter, fiber cables, may lead to very long repeaterless communication links.

Industry will take the lead in fiber optic cable fabrication development. The Navy will have to support the development of cables peculiar to its missions. The identification of families of needed cables and of electro-optical-mechanical splice terminations may speed up the development process.

Proposed Thrusts

U.S. Navy Report

Analysis/Design Current analytical models should be expanded to include three-dimensional techniques to gain a better understanding of stress levels and relative motions among cable structural elements in order to predict cable behavior and lifetime under various loading conditions. This model must include the effects of material properties, structural geometry, and all applied stresses. In particular, emphasis should be established using this prediction model. The model should be validated by the design, fabrication, and extensive testing of specific cables.

Connectors, Penetrators, and Terminations A data base of proven designs should be developed to improve the reliability of electromechanical connectors, penetrators, and terminations. These designs should include connectors for very high voltage (over 3,000 volts), unusually high mechanical strength or synthetic strength member terminations, wet mating by submersibles, swivels, sophisticated structures integrating sensors into the cables directly, and other special technologies that are not available as standard commercial items. The capability necessary for interfacing optical cables with other system elements through the development of components such as optical penetrators and connectors and slip rings for use with shipboard winches should be developed.

Repair A splicing and repair capability ought to be developed for complex electromechanical and electro-optical cables and terminations, with particular emphasis on field repair techniques.

Working Group Review/Workshop Comments

There are no major deviations with the Navy report. The following technical observations are presented for Navy consideration:

Analysis/Design Analytical model development must include predictions of cable function behavior as structural members are moved and stressed, i.e., variations in optical attenuation, electrical insulation, and acceptable voltage stress.

Realistic manufacturing performance specifications should be one of the goals of developing analytical models. Cable procurement specifiers will need to gain much of this knowledge to write sensible and cost-effective specifications.

These types of models, when developed by the manufacturing industry, will not generally be available in the open literature. Further, such models may not be applicable for the comparison of various manufacturers' cables. Models should not only provide information for guiding the writing of specifications. They also should provide information on cable life; both mechanical and signal degradation should be included in the developed model. Test data on cable life versus cable bend radius should be included.

<u>Data Base on Synthetic Materials</u> There is a need for a better materials data base on synthetic lines such as nylon and Kevlar. Such a data base should include both wet and dry properties and changes of properties during its life.

<u>Industry Development Components and Materials</u> As industry moves into deeper water, which they are doing, many more options to the expensive military specification (MIL SPEC) products will become available. The Navy should monitor these developments and only build to MIL SPEC as a last resort.

<u>Testing</u> A continuing problem is that of the need for nondestructive testing techniques that can be used through the life of a cable and by which criteria can be established for end-of-life cable retirement.

ROBOTICS, TELEOPERATORS, AND WORK SYSTEMS

U.S. Navy Report Excerpt

Scope

A. Controls
   1. Methods
      a. manual control
      b. supervisory control
      c. programmed control
      d. artificial intelligence
   2. Hardware
      a. sensors
      b. displays
      c. controllers

B. Manipulative devices
   1. Manipulators
      a. lightweight
      b. heavy duty
      c. construction
   2. Tools
      a. diver controlled
      b. remotely controlled

Objective

Develop and integrate the devices and techniques required to supplant man and improve on his capabilities to perform work, surveys, and data collection in operational areas that are normally denied to him.

Working Group Review/Workshop Comments **Considerable discussion regarding the Navy's overall, long-term objective under this research task of supplanting man with machines resulted in some agreement with this overall objective. Others saw such a concept as too ideal; a more realistic objective might be that of augmenting man with newly developed work systems.**

Related Technologies

Related technologies are: system dynamic response prediction; data transmission and handling; materials and structures; energy storage and conversion; nondestructive testing; sensors; and command and control.

DISCUSSION OF ROBOTICS, TELEOPERATORS, AND WORK SYSTEMS

State of the Art

U.S. Navy Report

Robotics systems range from simple manipulator to "supersmart" arms combined with sensors and automomous mobility. A common characteristic among these general systems is their capability of being programmed for specific tasks. Teleoperators also have sensors and actuators for mobility and/or manipulation, however, they are remotely controlled by a human operator in real time enabling him to extend his sensory motor functions to remote location. Work systems combine manipulators, tools, and auxiliarly equipment into remotely controlled devices to perform work, repair, emplacement, or recovery operations.

The state of the art in robotics systems is being driven by a nationwide emphasis from the industrial robotics community. Until now, the Navy's primary interest has been in the manufacturing technology areas and specifically automated shipbuilding programs -- although applications to search, inspection, work, and recovery were investigated. Teleoperator systems, used extensively on land and in space, require advancements in adapting components, especially sensors and actuators, for the ocean environment. Hydraulic manipulators using position control and force feedback are available for use in teleoperator and work systems. However, they do not have the dexterity, strength, controls, maintainability, and reliability to be compatible with future advanced systems. Underwater tools have historically been powered by pneumatic, electric, and hydraulic power sources. Hydraulic tools are preferred because of size, weight, depth restrictions, and hazards associated with pneumatic and electric tools for divers. Hydraulics also is the most common method of powering tools used on submersible vehicles.

Working Group Review/Workshop Comments

No exception is taken to the Navy's state-of-the art assessment. Several observations regarding motivation for development and development in this field are:

- **Teleoperator* development in the government has been led first by Navy needs and, in decreasing levels, by NASA, Army, and Marine requirements.**

***In this sense, teleoperator, in the most advanced stage, implies a high degree of work station logic under supervisory control.**

- **Industry does not use advanced teleoperators, except for specialized highly structured areas, such as nuclear hot cells and toxic/biological laboratories, and in some construction tasks.**

- **Activity in this technical area has been less in the oil and gas industry than in the Navy. Commercial contribution in this area has been mainly one of reliability improvement, force feedback development, and special training.**

- **There is considerable foreign development activity underway in France, the USSR, Japan, Great Britain, and in the Scandinavian countries.**

Forecast

U.S. Navy Report

The technology to implement robotic and advanced teleoperator systems is advancing at a rapid rate in industry. There is a critical need, however, to focus attention on the application of this technology to Navy requirements. Industrial applications of robotics will continue to increase, which will advance areas such as repetitious or programmable robots or manipulators, but this technology will fall far short of the base required for eventual autonomous systems. Space applications of robotic/teleoperator technology will probably provide the greatest advances, especially in the areas of control and sensors. Unfortunately, the ocean environment is quite different from that of space -- resulting in a large technology gap concerning the adaptation of these technologies to the ocean itself. The offshore oil industry is rapidly increasing its use of remotely operated vehicles for inspection and performance of very simple tasks, but this acceptance has been preceded by the effective use of such systems by the Navy. It is anticipated that acceptance of more advanced autonomous vehicles or sophisticated work systems will require initial development by the Navy, once again with industry drawing from that technology base. Academia is providing basic research in the area of autonomous systems and control techniques for application to manipulators and work systems, but this will require additional Navy support to adapt the research to actual undersea systems.

The ultimate goal of replacing divers with teleoperator systems and providing them with more advanced tool systems will not be achieved without initial development within the Navy. It is expected that industry would draw upon this technology once it has been developed. The Navy's present seawater hydraulic tool program will need to be augmented in areas such as submerged power sources and more efficient cutting and tearing techniques using cavitation, chemicals, or cyrogenic embrittlement.

Working Group Review/Workshop Comments

There are no major deviations from the Navy report, however, several technical observations are noted:

- **The rate of technical advancement in robotics is high, particularly in several foreign countries, but teleoperator development is not intense compared to the microelectronic field, for example.**

- **If there is no Navy infusion of funds, the development of teleoperators likely will be slow and evolutionary. The oil industry development is very gradual and does not promote high-risk research ventures in this technical area.**

- **Industry will not have the commercial interest to develop wide-area search, inspection, and recovery technologies. Navy efforts will receive little related technological transfer from industry.**

- **Replacing divers with teleoperator systems is a worthy but greatly ambitious objective.**

- **Usefulness of a human in the loop will continue to be appreciated for pattern recognition, and in deciding what to do and how to do it. However, university laboratories are developing ways to mix human and computer control to get the best out of both, i.e., supervisory control. This is especially promising for constrained bandwidth systems.**

Proposed Thrusts

U.S. Navy Report

<u>Controls</u> The integration of the computer allows use of more sophisticated control techniques essential to the effective development of future systems. The development and incorporation of supervisory control techniques, preprogrammed control, and artificial intelligence will allow the integration of future technologies into efficient, autonomous systems.

<u>Sensors</u> Sensors (i.e., visual, position, touch, force, proximity, and temperature) should be developed or adapted for use in future systems. Visual and position sensors are critical to most operations using either manual or programmed control techniques.

Manipulators Three classes of manipulators, including their mechanisms and controllers should be developed. Lightweight manipulators (0 to 23 kilograms of lift capability) with higher dexterity will be required for sophisticated tasks. Heavy duty arms (23 to 91 kilograms) will be required for general work operations, and large construction arms (91 kilograms plus) will be required for larger seafloor construction tasks.

Displays and Man-Machine Interface More sophisticated methods of presenting data to the operator need to be developed. The primary goal is to provide the operator with the data he needs, at the time he needs it, with little or no effort on his part.

Tools Although underwater tools exist, they do not meet the efficiency requirements of the future. Their overall power/weight ratio needs to be increased, while their size is reduced. They should be lightweight, safe, quiet, low-powered, and adaptable to diver or remote systems. The depth capability of tools (e.g., pyrotechnic torches), shaped charges, chemical milling, and explosive welding should be reliably increased.

Working Group Review/Workshop Comments

There are no major deviations with the Navy report, however, the Navy should consider the expansion of its thrusts. The Navy report lacks definitive statements of functional specifications for a range of typical requirements. These specifications need delineation before identifying system developments.

Under the various thrust categories, the following observations are noted:

Controls Passive force compliance at the end effector may have particular application to Navy tasks but would require task identification and development. Rendezvous and control with moving targets appear to be neglected areas of possible Navy concern, but this activity would require considerable research investment. Supervisory control technology is in a state of laboratory development that could be applied to operational problems. Since long-term, high-fidelity extension of vision, touch, and manipulation to an arbitrary point in space is not attainable in the near term, short-term milestones are needed. Master/slave, force-feedback systems need reevaluation for possible control application.

Sensors Touch sensing and control may likewise have application to robotic and teleoperator controls both in the areas of autoreflexive action and for display to operators. Force function is more important than is indicated in the report, but it is of secondary importance compared to vision.

<u>Displays and Man-Machine Interface</u> Since object geometry, and sometimes environmental objects, are known, there are many possibilities for using computer graphic aids to augment (even mix) video displays. This is similar to "head-up" display in aircraft.

CONTROL GROUP

Command and control and navigation, the two technologies discussed in this section, are an extension of the data/information acquisition, processing, and transmission considerations discussed in the previous section. The separation of these technologies is maintained since one group of experts reviewed these technologies as a unit. The process used in the workshop analyses combined the technologies in this section with those in data systems.

COMMAND AND CONTROL

U.S. Navy Report Excerpt

Scope

A. Adaptive
B. Servo components (including actuators)
C. Control algorithms
   1. Feedback control
D. Monitor and display

Objective

Develop techniques for integration of data to permit action in response to changing conditions while providing meaningful and accurate status information.

Related Technologies

Related technologies are: system dynamic response prediction; moorings; data transmission and handling; robotics, teleoperators, and work systems; sensors; anu cables.

<u>Working Group Review/Workshop Comments</u> **Sophisticated command and control techniques exist elsewhere both within and outside the Navy; for example, shipboard weapon fire control systems, aircraft control, and space craft manipulator controls. The techniques developed should be investigated and monitored for applicability in deep ocean engineering. As the Navy report gave few details of the envisaged command and control problems, comments are brief on both the forecasts of technologies relevant to Navy benefit as well as to the identification of technology gaps in the proposed Navy thrusts.**

DISCUSSION OF COMMAND AND CONTROL

State of the Art

U.S. Navy Report

Command and control systems in their most general sense are the closed-loop systems which include the communication link, sensors, computers, displays, control system, actuators, and the man necessary to accomplish certain tasks in near real time. Such a system might include several closed loops to accomplish its purpose. Simple systems may appear to lack certain elements. For example, a closed-loop, computer- controlled system may lack the man and the display. Nevertheless, the computer software is the man's surrogate in accomplishing certain preprogrammed tasks which are triggered by events or a time-out feature.

Computer systems have been developed from simple analog devices to powerful digital computers with relatively inexpensive very large-scale integrated circuits, memory, and control processors. The microprocessor permits powerful computations to be made undersea. Presently, 16-bit microprocessors are available, and 32-bit microprocessors will be available shortly. In the area of software, powerful algorithms such as fast Fourier transforms, digital filters, correlation techniques, and pattern recognition, are available to assist the man in processing data.

Underwater sensors include low-light level television, sonar, magnetometers, touch sensors, attitude sensors, environmental sensors, and other engineering sensors. For communications, simple wire links are available as well as optical and acoustic links. Radio frequency links have limited range but are useful for a few applications. In the area of displays, the CRT is still the workhorse unit, although plasma displays have certain advantages such as they can be organized naturally for digital techniques. Electroluminescence, light emitting diodes, meters, printers, and indicating lights are other displays that are useful.

Working Group Review/Workshop Comments

There are no major deviations from the Navy report. Much of the state of the art cited is not peculiar to deep ocean technology. In some cases, the offshore and space industries have addressed similar problems.

Forecast

U.S. Navy Report

Significant progress may be expected in the command and control areas, however, most of this will be directed at land-based objectives. The following are areas where progress is expected. Much progress has been made in recognizing man-made objects from circumferential and elastic wave signatures. More progress may be expected in recognizing live submarines and mines using these techniques. None of this technology, however, will be directed to searching for lost submarines or aircraft unless a special effort is made to do so. Powerful analytical tools such as pattern recognition algorithms, Kalman filters, and fast Fourier transforms are presently available. With the progress in developing VLSIC, many of these analytical tools may be expected to be implemented on a single chip. The combination of powerful 32-bit microcomputers, 64-bit microcomputers, and VLSIC will permit parallel processing in near real time by a combination of software and firmware. Various transform techniques can be applied to data to manipulate it into a form which a human can better understand and recognize by the use of interactive graphic displays. These displays can employ color and three-dimensional capabilities to aid the operator better. Greater use of predictor techniques, such as the Kalman filter, may be expected to make systems adaptive and to make them more reliable by permitting a system to reconfigure itself automatically when major failures occur. Optimal control theory and algorithms employing full state feedback will be employed to make systems adaptive in environmental conditions. Although much progress can be expected, the areas of undersea and work systems require Navy sponsorship to overcome the specialized undersea problems.

Working Group Review/Workshop Comments

There are no major deviations from the Navy report, however, the following points concern probable trends:

- **Intense foreign competition will continue to exist in the development of underwater command and control systems; foreign countries that are leaders in this effort are France, Great Britain, and Japan.**

- **The Navy will need systems having a greater endurance and depth capability compared to those systems likely to be developed industrially. In the opinion of the working group, only Navy participation will further the development of adaptive control systems for deep ocean work.**

- **The Navy report was not explicit in detailing its unique requirements. However, based on its presumptions of Navy needs in command and control, the working group felt that industry will not address technologies of major concern to the Navy.**

Proposed Thrusts

U.S. Navy Report

Search and inspection techniques that employ sophisticated signal processing, pattern recognition, and artificial intelligence techniques should be developed. By use of these techniques, appropriate display cues, and man-machine interaction, the machine can significantly aid man in the search and inspection operation. Ultimately, these techniques may be used in an autonomous vehicle for search and inspection without the need for a man.

Techniques should be developed that make systems adaptive, more reliable, and capable of reconfiguration when monitoring equipment discovers a fault or an incipient fault. Promising techniques, which are being investigated using basic research funding, include Kalman filters and modern control theory employing the state variable in multivariable input/output systems. Powerful microprocessors, efficient algorithms, and large-scale integrated circuits will permit this technology to be used in real time in underwater systems.

Techniques should be developed which employ touch sensors, optical sensors, sophisticated signal processing, pattern recognition, and artificial intelligence to assist man in performing underwater work. By use of these techniques together with other cues, such as sophisticated graphic display techniques, and remote feel and sound innovations, the machine can significantly aid man in performing work. Optimal control algorithms, full state feedback, and adaptive control techniques should be employed to make work systems dexterous and flexible. Ultimately, these techniques may be used by a robot in the sea with minimum supervisory control by man.

Working Group Review/Workshop Comments

The Navy's thrusts are too restrictive in only supporting search and inspection missions and thus may be deficient in providing support technologies for other deep ocean missions, such as special salvage and recovery operations.

The following comments regard specific thrusts:

Supervisory Control Underwater inspection and manipulation can be enhanced by use of supervisory control. This is a hierarchy of three control loops, the first being a man on the surface communicating instructions and receiving processed information from a computer on the surface, the second being a computer on the surface communicating with a computer in a remote undersea vehicle, and the third being computer control and processing of the remote computer in a control loop with sensors and vehicle thrusters on manipulators. This is seen as a means to perform deep ocean operations without hazard to man, to do so over acoustic telemetry channels which may have extreme bandwidth constraints or time delays, and to allow operations without continuous monitoring by the operator.

Command Language Higher level command language is needed so that supervisors can direct tasks by communicating task objectives to the remote vehicle rather than by the present operator-fatiguing, continuous guidance techniques. Use of macro languages, with linkages to on-board program modules for individual tasks, would provide a basis for computer implementation of remote vehicle movement and work tasks.

Error Correction There is a need for technology advances to enable remotely operated vehicles to detect their own errors and make corrections to control functions. This capability would require on-board analysis of sensory systems environmental data and navigational data which, can be compared with on-board computer memory and pre-programmed models to provide correction signals. New technology from the process control industry can be modified for use in undersea operations.

Reducing and Combining Vehicle-Manipulator Degrees of Freedom A better understanding is needed of how to coordinate vehicle control and manipulator control avoiding redundant and costly degrees of freedom. (It has been estimated that the cost of a manipulator doubles for each added degree of freedom.)

Tether-Free System Free-swimming vehicles are constrained by battery power and need to be charged up periodically. Tethered vehicles have long endurance but are constrained. They could work together, where the latter feeds the former, but concepts need to be identified, evaluated, and developed on how to effect this coordination. Multiple free swimmers could be fed from one tethered vehicle.

Multisensor System For sensing and manipulation in very turbid water, rugged touch sensors need to be developed, since optical and, to some extent, acoustical sensors are severely limited there. Improved means of integrating information gleaned from touch sensors and from sonar sensors are needed.

<u>Simulation Systems</u> Simulation systems are needed which integrate combined data and information which affects vehicle performance, including the influence of hydrodynamics, thrust control, sonar and other sensing, manipulation, and constraints of cables and tethers.

<u>Nontethered Elements</u> The Navy should encourage technology development for command and control for nontethered vehicles and work systems.

<u>Pattern Recognition Problems</u> A strong, determined effort will be required to solve the types of pattern recognition problems that needed to be addressed in deep-sea technology applications.

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NAVIGATION

U.S. Navy Report Excerpt

Scope

A. Magnetic
B. Acoustic
C. Inertial
D. Satellite
E. Radio Frequency
F. Celestial
G. Optical

Objective

Develop, integrate, and validate improved navigational equipment and techniques.

Working Group Review/Workshop Comments The Navy report did not specify a range of accuracies needed for its deep sea technology missions nor the operational restraints involved, thus making the assessment of the adequacy of the planning difficult. The working group substituted its general understanding of the Navy's navigation needs.

Related Technologies

Related technologies are: moorings; nondestructive testing; sensors; and geotechnics.

DISCUSSION OF NAVIGATION

State of the Art

U.S. Navy Report

For ocean engineering purposes, navigational systems may best be categorized in terms of those that are useful above water and those that are useful below water. The following is a brief discussion of systems falling into these categories.

Above Water Systems Most of the high accuracy systems operate in the megahertz or microwave area and have a range that is basically line of sight. Accuracies as good as 1 meter are achieved. Typical systems which are available include Maxiran, Syledis, Trident III, Shoran, Moran, Artemis, Autotape, Electrotape, Miniran, Miniranger, Tellurometer, Trisponder, Prans, Lorac, Raydist, and OMI.

Since these systems are line of sight, they are short-range systems. Exceptions, of course, are those systems which are deployed from satellites such as Satnav or the Global Positioning System (GPS). GPS will be a worldwide system using 24 satellites to give continuous all weather coverage of the earth. Potential accuracy is 5 meters. Radio frequency systems at low frequency and very low frequency give reasonably good ranges, but accuracy is low. Typical systems include Decca, Loran-C, and Omega. Omega is a worldwide system, but it has an accuracy of 1.6 to 3.2 kilometers. Visual and infrared techniques may be used to obtain accuracies of a few centimeters. Specific systems which are available include Minitape HDM-70 and Geodimeter.

Below Water Systems Most of the underwater systems employ acoustic techniques to obtain range and bearing. Long baseline systems achieve good accuracy by using transducers on buoys. Short baseline systems employ hull-mounted multitransducers, whereas ultrashort baseline systems employ a single transducer. A typical system is a Honeywell RS904 that employs a microprocessor and has an accuracy of 1 meter in 100 meters of slant range and 5 degrees in azimuth.

Various inertial systems are useful for underwater work, however, standard gyros drift at an unacceptable rate for underwater work. Therefore, it is common practice to employ hybrid systems that aid in the inertial system in achieving better accuracies. A typical underwater aid would be an acoustic Doppler system to permit the inertial system to achieve a better accuracy than it could achieve by itself.

Pseuodorandom noise (PRN) navigation techniques have been developed for precise navigation on and above the ocean surface. PRN has also been used undersea but not for navigational purposes. Acoustic recognition of objects such as spheres and cylinders has been accomplished in water using their elastic wave signatures when interrogated by wide bandwidth pulses. Additionally, pattern recognition techniques have been employed to characterize and recognize man-made objects from undersea photographs using features such as shape and texture. Contour following techniques have been developed for navigation above land areas. None of these techniques have been developed for navigation in the sea, and no navigational development is anticipated using these techniques unless the Navy sponsors such development in the future.

Working Group Review/Workshop Comments

The Navy report underestimates the available capabilities of inertial systems. The technology is available for meeting most mission needs. However, inertial navigation systems have not been developed for submersibles due to constraints in size, drift and update requirements, and cost. For many years, the Navy has used gyros, as well as other methods for accurate navigation, in the fleet ballistic missile program.

Forecast

U.S. Navy Report

Inertial systems are being developed which are small and very accurate since drift rates are low. Additionally, some of these systems consume very little power. Electrostatically suspended gyro (ESG) systems are of particular interest because of their attractive performance characteristics, such as accuracy, size, and power consumption, for small undersea vehicles. Laser gyro systems are also replacing standard inertial systems due to superior cost and reliability performance characteristics. Laser gyros are being used on aircraft.

The GPS is expected to be operational within the next decade. The Illinois Institute of Technology was funded by the Air Force to produce eight receivers. Although nothing available yet commercially, commercial receivers undoubtedly will be available if GPS meets the expected performance goals.

Retransmission techniques may be expected to be employed to eliminate propagation errors for RF signals in such systems as Loran-C, and Decca. Retransmission is a technique where propagation variations are eliminated by use of a local monitoring station which is sited accurately. A vehicle whose position is to be measured retransmits the radio navigation signal which is received by the local monitoring station. Since the monitor is at a known position, it can determine variations in propagation and correct the vehicle's apparent position.

Working Group Review/Workshop Comments

There are no major deviations from the Navy report but the following observations are made:

- **The electrostatically suspended gyro system has a serious drawback in that calibration times are long and involved.**

- **Retransmission techniques will not be developed except for very special purposes.**

- **Leadership in the United States in underwater navigation is military driven; little input will come from industry sponsorship. New technology in this area also will be developed in other high technology based western countries.**

Proposed Thrusts

U.S. Navy Report

Since inertial navigation is one of the few techniques which may be used under the ice, an ESG or laser gyro may be attractive for use on an undersea vehicle. Work is continuing at this time on these inertial systems. Although the performance parameters are outstanding, the cost of a single unit with software is still high. A study should be made of both ESG and laser gyro systems with appropriate navigational aids, such as acoustic Doppler, to determine what type of system would be most cost effective for appropriate missions for a small submersible. The study should consider such problems as calibration at sea. Depending on the results of the study, a system should be procured and tested in a submersible.

Omega navigation at shallow depths from a submersible should be tested. Omega is a VLF system and can be received at shallow depths of approximately 15 meters. The test should be conducted over one land width (113 kilometers) to provide that the system can operate from one unambiguous lane to the next. Omega navigation can also be useful for navigation under the ice.

The concept of machine recognition of sea bottom markers at fixed known geodetic points should be demonstrated. For long cruises (such as under the ice) an autonomous vehicle would navigate to the vicinity of this marker (a way station) using inertial navigation, contour recognition, and conventional acoustic search sensors. It would then use other sensors to search for the marker and navigate within a few yards of the marker where it would update its inertial system to the exact geodetic position and use a Kalman filter to update other states (velocity and tilt errors). At least two approaches are available. The first approach would interrogate and navigate to a marker beacon using pseudorandom noise codes. The second approach would use a passive marker in the shape of a sphere that exhibits characteristic circumferential and elastic wave signatures in response to a wideband pulse from the vehicle. This signature can be recognized by a computer on the vehicle. Further verification may be made by employing a television camera to obtain visual data. By pattern recognition techniques, the computer can verify the sphere by shape and texture.

Precise navigation should be obtained and inertial navigation should be updated by the use of the GPS. For long cruises, an autonomous vehicle would occasionally rise to the surface and use a helix antenna to obtain a GPS fix. It would then update the inertial system to the exact position determined by the GPS. Other states such as velocity and tilt errors would be updated by use of a Kalman filter.

Working Group Review/Workshop Comments

There are no major deviations from the Navy report but the following observations are made:

- **Several technical capabilities that are mentioned in the proposed thrusts are of particular concern to the working group and should be considered for emphasis: under ice navigation; high latitude navigation; large area subsurface navigation (150 kilometers range); and accurate, local navigation (for use by ROVs or divers within and around sunken ship hulls and salvage sites).**

- **Less concern for miniaturization, where not absolutely needed, may reduce costs and speed up project completion.**

- **It is doubtful that a "various-mission" study will produce sufficiently well-defined specifications required for procurement.**

- **Coupling of the GPS to subsurface units will require development. Alternatives to GPS should be considered, for example, subsurface acoustic Loran or Raydist.**

- Embryonic technologies for many applications exist but will need project support for conversion to applied research. These applications include contour following techniques and man-made markers which may be detected by their fields or through interrogation.

- Several Navy R&D programs should be monitored for fallout to the Navy deep ocean needs: Correlation Sonar (General Electric); Trident Velocity Sensor Program; and Minehunting Navigation System (PINS).

DYNAMICS GROUP

Most of the objectives for the three technologies in this section address the Navy's capability to analyze, predict performance, and determine the criteria for design or procurement of critical undersea systems and components. System dynamic response prediction, load handling, and understanding and improving moorings, which are topics discussed in this section, are closely interrelated and were assessed by one working group. Additional attention is also given to moorings and cables materials development in the earlier data systems discussion.

SYSTEM DYNAMIC RESPONSE PREDICTION

Navy Report Excerpt

Scope

A. Components
   1. Cables
   2. Structures
   3. Fluids

B. Systems
   1. Surface support
   2. Subsurface
   3. Towed

C. Environmental
   1. Weather
   2. Sea state
   3. Currents
   4. Seafloor

Working Group Review/Workshop Comments Within the scope, consideration should be broadened to applications included in the arctic environment, which in turn refers to the environmental conditions of complete ice cover (marginal ice pack), partial ice cover (marginal ice zone), and adjacent free surface areas (especially fetch-limited water). The scope also refers to arctic currents and eddies which differ significantly in temporal and spatial scale from the open oceans.

Objective

Develop techniques and analytic methodologies to specify and accurately predict system and environmental dynamics for ocean engineering applications.

Related Technologies

Related technologies are: moorings; load handling; robotics, teleoperators, and work systems; command and control; materials and structures; and geotechnics.

DISCUSSION OF SYSTEM DYNAMIC RESPONSE PREDICTION

State of the Art

U.S. Navy Report

This technology deals specifically with methods for analyzing the response of ocean engineering equipment to random forcing functions. Operational difficulties and system failures are often the result of dynamic response to surface waves, wind, or currents; frequently forces or displacements of ocean engineering systems are many times those expected under steady state conditions. Prediction of the dyna-mic behavior of equipment at sea is, therefore, critical to ocean engineering applications. The development of accurate analysis techniques will allow safe operation under more severe conditions through the improved design of control systems or structural components.

Prediction is statistically based when applied to design or operational planning. Generalized input such as sea state spectra is applied to a system response operator to predict a spectrum of system motions. The analytic methodology exists for statistical predictions of subsystem dynamics, such as ship and cable motions. Estimates of ship motion are calculated by using ship characteristics and sea state models. There is at least one commercial system for statistically predicting barge motion in real time. Analysis of the dynamic behavior of subsea cables can be performed with existing techniques; however, minimal validation exists.

Analyses of the dynamics of systems such as ship-crane cable combinations are feasible, but they are presently limited to the application of linearized response operators. The accuracy of such approximations has not been established.

Dynamic analysis as a design tool is used in the offshore oil industry in many projects. Where structural programs such as NASTRAN are applied to major structures, the predictions are good. Little success is noted, however, in modeling complex equipment such as actively controlled motion compensation systems. Nonlinear dynamic analysis as a design tool for total systems or complex subsystems is virtually unknown in military ocean engineering.

In addition to statistical prediction, the capability to predict system dynamics spatially and in real time has been briefly demon-strated. Specific ship motion has been predicted in real time up to 4 seconds before occurrence. This type of analysis is particularly appropriate to submersible launch/recovery systems, load handling, motion compensation, and aircraft carrier landing systems.

Analyses require accurate descriptions of the environmental forces. Weather and sea state data and predictions generally have been adequate for most applications. However, subsurface currents are not well-defined below 100 meters except for areas where extensive data have been taken. The effect of bottom topography on currents is not considered by existing analyses.

Working Group Review/Workshop Comments

The Navy report statements are basically accurate but deserve some expansion for several specific response prediction objectives. References 1 through 8 are generally applicable throughout this section.

<u>Long-term response prediction for design and operational planning for structures and vessels excited principally by waves</u> Long-term (defined as relative to system life) statistics are commonly desired by the designers. Frequency domain linear transfer function techniques are commonly used in the Navy and the offshore oil industry. For low sea states and simple systems, such as single vessels or platforms, the results are generally acceptable. Problem areas do exist, such as:

- The directional spreading of waves is not adequately accounted for in these systems. The significance of directional wave spreading on predicted dynamic response of a tension leg platform has been demonstrated.[9]

- In higher sea states, wave nonlinearities are not usually accounted for, nor are nonlinearities resulting from fluid-structure interaction. Research in wave nonlinearities is active*, following the Benjamin-Feir mechanisms.[8] This mechanism traces spectral broadening, amplitude growth, and decay associated with initially small perturbations in the wave field.

- Although many dynamic response calculations are computed for design purposes, the results are rarely validated with follow-up, at-sea data collection.

*Investigators include Drs. W. K. Melville, D. J. Benney, and E. L. Mollo-Christensen, Massachusetts Institute of Technology; Longuet-Higgins, Cambridge University, England; G. B. Witham, California Institute of Technology; and M. Stiassnie, Technion, Haifa, Israel.

- Even in low sea states, the prediction of long-term response statistics for complex systems is inadequate. A common weakness is the poor understanding of damping mechanisms, and even more serious is the inability to predict damping when it is known to be significant. The offshore oil industry has very similar needs with respect to damping and will be a valuable source of advances in the technology. Cook and Vandiver give examples of the significance of damping in their work on dynamic response prediction.[9, 10]

- Fatigue life calculations based on long-term response statistics are unverified at present and have many sources of uncertainty. The understanding of materials behavior in seawater has many weaknesses; the section in this report on materials and structures contains more details. The prediction of stress statistics based on dynamic response also has many sources of uncertainty. The effect on fatigue of these uncertainties has been discussed by Kawamoto et al., Kinra and Marshall, and Vandiver.[11-13] The oil industry is encouraging extensive research on fatigue.

Short-term response to surface waves Here short-term response relates to operational conditions of less than or of the order of one day. The objective may be prediction of the response spectrum of a vessel on a next day basis for operational planning or adjustment of multiple mooring tensions for the next hour. Simple linear models do work well for low sea state unidirectional wave cases. Again, nonlinearities and wave spreading present problems.

The oil industry has the capability to do time domain finite element integration of motion equations for fixed structures including some fluid and structure nonlinearities (see references at the end of this section). Again, there are weaknesses in the area of prediction of complex coupled response of ship-crane-cable load combinations.

Real-time prediction or anticipation For applications such as aircraft carrier flight operations or crane-barge operations, the capability of predicting the response in the future on a real-time basis is desirable. Some success has been achieved, but much more work remains to be done. Advances require real-time sensing of surface wave conditions including directional characteristics.

Large displacement and small displacement cable motion due to currents Large displacements are taken to be of the order of catenaries, small displacements of the order of cable element diameters. Dynamic response analysis must usually begin with a reasonably good static configuration. The static configuration of a mooring, for example, depends on the local currents and the small displacement motions. The small displacement motions are usually called cable strumming and result from vortex shedding. For short, taut cables in uniform currents, the small displacements and their related drag coefficients can be reasonably calculated.

For longer cables with sag, or in spatially varying currents, the vibration response cannot be adequately predicted at present. In turn, the drag coefficients cannot be accurately predicted because they depend on local response amplitudes. Because of the poor predictability, the static position is poorly known. Considerable work remains to be done in this area.

A large body of reference material of flow-induced vibration exists, and there is extensive knowledge of this literature at the Naval Research Laboratory (Owen Griffin, Richard Skop, Steven Ramberg) and at the Naval Civil Engineering Laboratory (NCEL) (Dallas Megget, William Nordell, Jerry Dummer) The Office of Naval Research and NCEL have supported substantial research in this area.

Data bases The environmental data bases with respect to wave spectra, direction, and currents are inadequate to support their analyses. Similarly, validating data on existing designs is seldom taken.

Crane operations Crane operations are hampered by lack of advanced training of operators. Simulation facilities, analagous to those used in aircraft and ship pilot training, probably do not exist or are not used routinely.

Arctic environmental descriptions Since 1970, considerable knowledge has developed in central arctic environmental descriptions. This knowledge pertains to static and dynamic loads. Models and predictive capabilities exist for ice thickness,[14] ice stress,[15] arctic eddies, and currents.[16] Ice morphology also has been described by Wadhams.[17] There are limitations: winter effects are better understood than summer; marginal ice zones are not yet understood nor are open waters near ice edges; and, ice statistics (other than mean thickness) are not yet modeled.

Offshore oil companies are developing methodologies for ice-ship dynamic interactions (especially the Dome Arctic Pilot Project of Canada, icebreakers in Norway, and ice-platform dynamic interaction by Shell, Sohio, and Exxon in the United States and Dome in Canada).

Forecast

U.S. Navy Report

Sea state models and the analysis of ship motions will continue to be refined to meet both offshore oil industry and Navy requirements. The dynamic response of other systems will continue to be analyzed on a project basis. The primary application will be the transfer of payloads between platforms with relative motion by offshore supply system designers. It is not expected that general methodologies will be developed or even that specific modeling techniques will be made available from nongovernment sources. This lack of general modeling capability effectively will prevent optimization of most common systems. Operations will often be conducted in ignorance of equipment limitations.

Real-time spatial motion prediction will remain undeveloped except for some specific applications.

The design and operation of ocean systems will continue to be addressed separately. Methods for monitoring ocean operations will not be considered as part of the system design nor will the design model, if developed, be verified or used to optimize performance.

Working Group Review/Workshop Comments

The Navy report identifies the expected continuing development of sea state and ship motion analysis models by both the offshore petroleum industry and the Navy. The document notes that although the general framework of systems analysis will be applicable to one-of-a-kind systems, a need will always exist to analyze these on a project by project basis. The evaluation appears to be influenced by the stated restriction that transfer of payloads at sea will be the primary application of system dynamic response. There are, however, important existing and potential Naval applications that require attention to other facets of system dynamic response prediction. For example, low-cycle and high-cycle fatigue are subjects of large efforts by the offshore industry, particularly directed to large fixed and floating structures. The information is not typically proprietary and consequently is generally available for transfer to Naval applications.

More realistic representation of the sea state and systems will be required. In particular, the nonlinearities of the sea state and the system will be accounted for in the designs and will be identified in the measurements. In design, it will become increasingly practicable, using models of nonlinear waves, to evaluate the need to include their effects in any particular application. In addition, the directional properties of the waves will become recognized as more important, particularly in vessel roll motions.

Research active in academic and research institutions in the United States and the United Kingdom on nonlinear wave mechanisms will likely lead to extrapolative understanding (e.g., engineering predictions) of high sea state effects. Such results are now on the horizon and will likely be of practical use by 1990-1995.[1-3]

Basic research communities in the United States and abroad (United Kingdom, Canada, Norway, France, West Germany, Denmark) will expand and improve ice dynamic models to include marginal ice zones, adjacent waters, and all seasons. Useful predictive capability will be available by 1990.

The offshore industry will continue to develop special systems for arctic operations. These systems will reach a mature plateau by 1995.

The technology will exist to develop instrumentation packages which could be installed on vessels to measure the appropriate sea state characteristics. These would probably be remote sensing systems having the ability to "look upwave" to provide input to real-time motion prediction. Development of new methods and refinements of existing methods will be accompanied by more full-scale testing, designed specifically to verify the developments. The increasing presence of on-board computing systems will be evident in more vessels including instrumentation to monitor their motions and the associated environmental forces. The leadership in application may be expected in the offshore industry because of the increasingly high cost of lost time in drilling and production operations. However, the relatively limited market for the instrumentation (number of sensors) may inhibit commercial development.

Proposed Thrusts

U.S. Navy Report

A dynamic analysis methodology that is sufficiently general should be developed for a variety of ocean engineering applications. This capability should be extended to provide quasi-real-time analysis of system dynamics. This will permit accurate design and planning to enlarge environmental operating windows and to improve safety.

The capability to predict spatial motions in real time must be developed and verified.

The development of ocean current prediction techniques or models should be emphasized. These techniques or models should account for the complex interaction of the water mass and the bottom topography.

Working Group Review/Workshop Comments

General dynamic analysis methodologies that treat the load-cable-crane-ship system should be developed for a variety of ocean engineering applications. These analyses should provide long-term statistical predictions for design and operations planning, on-scene

(one hour/area) statistical prediction for operations in progress, and real-time predictions up to several dominant wave periods ahead. These analytical models will permit accurate design and planning as well as the development and operation of motion compensating devices. Thus safety will be increased and environmental restrictions mitigated (i.e., the time period for acceptable operational conditions can be increased). The objective requires that present subsystem models be integrated with the additional consideration of nonlinear forces between the cable and the ship, and hydrodynamic forces between the ship and load when it is in the water surface. Directional wave spectra and nonlinear wave dynamics at high sea states must also be addressed. The validation by experiment of predictive models should not be neglected in the future thrusts.

The advent of bottom-mounted flexible towers in the offshore industry implies a potential application in naval basins and support operations. Dynamic analysis techniques for these complex coupled systems must be developed including those with buoyancy provisions to create sections in tension, and their guy cables which also may be buoyant. Unless earlier requirements occur in the Navy, this thrust may evolve in the industry.

While some arctic developments will occur in industry as noted in prior discussion, a thrust by the Navy needs to be developed for load transfer from an ice surface platform to a submerged vehicle or sensor system. Similarly, transfer from a submerged vehicle or platform to other submerged vehicles or systems must be considered. Techniques are required to account for ice stress, ice thickness and roughness, ice drift, ice deformation, variable ice cover, strong near-surface eddies, and internal waves. In addition, high- and low-rate ice failure models along with plastic deformation models are needed for predicting ice and structure interaction.

Analysis methodologies should be developed which can be easily applied. Their increasing use as design and operational tools makes it important that test problems be established and run, documentation standardized, and error-proneness minimized. The effort is not likely to be developed by industry since there is little market incentive. A similar thrust is advocated in the report of the International Ship Structure Congress, 1982.[18] SEADYN is an example of the development of an easily applied program. This comment is noted to have a cross technology application in load control software.

Methods should be devised to use the statistical dynamic analyses mentioned above as inputs to structural fatigue models, and extensive experimental programs should be undertaken to test fatigue life predictions. As noted, an industry lead may be expected in the methodology, but the verification programs lag or are neglected unless a catastrophe occurs.

In addition to fatigue, a thrust is needed for experimental and theoretical programs to gain a predictive capability for small displacement motions of long cables. Again, the experimental effort requires emphasis by the Navy.

The Navy should develop dynamic simulation programs and application to the training of crane operators in at-sea load handling. The training aspects of the man-machine interface is well precedented in other fields.

It is noted, in regard to the above comments on validation or verification programs, that some data exist largely unnoticed and worthy of retroactive thrust. A deep mooring experiment at NCEL provides an example.[19]

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LOAD HANDLING

U.S. Navy Report Excerpt

Scope

A. Air/Sea Interface
   1. Launch
   2. Recovery
   3. Motion compensation
   4. Tension control
   5. Transfer (includes towing, pumping, roll-on/roll-off, etc.)

B. Subsea
   1. Emplacement
   2. Recovery
   3. Movement
   4. Transfer (includes towing, pumping, air lifting, etc.)

Objective

Develop techniques to permit the analysis, prediction, and design of controlled handling for any type of load, both on the surface of and at any depth in the world's oceans.

Related Technologies

Related technologies are: system dynamic response prediction; moorings; materials and structures; nondestructive testing; sensors; geotechnics; and cables.

DISCUSSION OF LOAD HANDLING

State of the Art

U.S. Navy Report

Currently available underway replenishment technology permits horizontal handling and transfer of relatively lightweight loads (6 metric tons or less) and low viscosity liquid cargoes in sea states 5 and below. Vertical transfer and handling of lightweight and medium loads (60 metric tons or less) through and below the air/sea interface are limited to sea states 3 and below using cranes outfitted with devices to control load pendulation and motion. Handling of heavy loads (60 to 1,000 metric tons), both horizontally and vertically, above, below, and through air/sea interface is limited to sea states 2 and below in protected waters using marine cranes and elevator platforms. It is also possible to eliminate snap loads during open ocean handling of loads up to 15 metric tons as well as to transfer various size and weight loads between offshore platforms and offshore supply boats. However, the majority of these systems are massive and complex. Systems and techniques have been developed to permit the direct drive-off of vehicular loads via offloading ramps in established ports.

Working Group Review/Workshop Comments

There are no major deviations from the Navy report, but several observations are made. A major problem in the load handling area is that the equipment is inherently massive, complex, and expensive. This is a consequence of the loads induced by motion caused by waves at the air/sea interface and the high powers required to compensate for these motions. Towing is a means of load handling. The design and operation of towing systems is presently an art, however, towing is a technologically feasible method for delivery or transfer of deep ocean loads.

The Navy report does not specifically refer to salvage operations and notes loads to 1,000 metric tons only. The status of salvage capabilities in the United States has recently been reviewed in depth, at the request of the Navy.[1] The capability was not analyzed in specific terms of heavy lift requirements at sea such as recovery of military losses. However, time-critical operations, such as rescue towing in bad weather and cargo transfer, were among the concerns noted.

Forecast

U.S. Navy Report

The offshore industry will continue to improve their platform-supply boat transfer systems. Marine cranes will continue to be improved. However, both industries are not greatly concerned with reducing the size and weight of system components. The heavy marine crane industry is relatively unconcerned with motion compensation. Liquid cargo offloading systems will be improved to handle more viscous fluids; however, little will be done to address hazardous substance transfer and dry bulk cargo transfer. There will be improvement in launch and recovery handling systems for manned and unmanned vehicles. Increased military emphasis on the use of containers, container ships, and roll-on/roll-off ships will cause improvements in lift-off techniques and the development of military vehicular cargo drive-off techniques for offshore ship offloading operations. Most of the above will be little concerned with the problems resulting from working through the air/sea interface. No effort will be made in the area of subsurface towing. No significant effort will be made to understand the mechanical and structural properties of wire rope, synthetic lines, and composite cables. Little will be done in the areas of subsea emplacement, recovery, movement, and transfer.

Working Group Review/Workshop Comments

The general thrust of the Navy's forecast statement is that the marine industry will continue to improve cargo and load transfer capabilities but will not emphasize reduction of size and weight. The working group has some reservation to the latter statement since the sizes and weights will be dictated by loading, power, and materials. Economies of production and logistics will force industry attention to this item.

The offshore industry will continue to address the problem of subsurface and through-the-surface handling of large and heavy loads using specialized equipment. While this technology may satisfy some particular applications, industry is unlikely to address the problem related to load handling and subsea emplacement of equipment of the size or type of interest to the Navy. The range of water depths and the equipments typical of Navy deployment will continue to be special problems.

Exception is taken to the statement that no significant effort will be made to understand the mechanical and structural properties of wire rope. A significant body of theory and data exists in this area, but there has been little accomplished in application of this data base (see Appendix C).

The oceanographic institutions will provide incremental advances in the art of subsea emplacement as a natural improvement of their mission capabilities. Since they are primarily supported by the Navy, the channels exist for technical transfer of the results of research.

Proposed Thrusts

U.S. Navy Report

Dynamics An intensive effort should be made to understand thoroughly the basic theory and characteristics of load handling (including towing) in a dynamic environment. Both horizontal and vertical movements should be addressed for the three general regimes with which the Navy is concerned: above the air/sea interface, through the air/sea interface, and below the air/sea interface. This requires the ability to predict and analyze accurately sea states as well as support platform motions in any combination of wind, sea, and current. It is imperative that a complete understanding of all types of cables (i.e., wire rope, synthetic, composite, electromechanical) be obtained in areas such as construction, mechanical and structural properties under load, environmental effects (i.e., abrasion, ultraviolet light, oil and chemicals, seawater, sand, rust), fatigue, and bending. To accomplish this will require the development of new analytical techniques, new instrumentation, new testing facilities, and new testing techniques. Appropriate similar efforts should be made for drillstrings. Also necessary is an investigation into the behavior of irregularly shaped masses (including the influence of added mass) under the effects of wind, sea, and current. Investigation and analysis of composite subsea handling techniques, such as pontoons/ lift wires and foam/lift wires, also should be undertaken.

The theory, characteristics, and techniques of handling and transferring liquid and dry bulk cargoes ought to be developed. Both horizontal and vertical movement should be addressed above, below, and through the air/sea interface. This effort also should include as an important subset the rapid and efficient handling of containerized and palletized cargoes to support amphibious operations as well as major, long-term invasion operations in the absence of adequate port facilities.

Sufficient data must be collected to validate the above developed theories, characteristics, and techniques.

Working Group Review/Workshop Comments

Dynamics The breadth of the statement with respect to "complete understanding" of all types of cables reduces the overall credibility of the recommendation. Certainly, dynamics and modeling are well understood with the exceptions of nonlinear interactions. The problem

areas for specific applications are in the lack of data relating to hydrodynamic coefficients, structural characteristics, or damping, and in lack of models and data on nonlinear hydroelastic interactions. Also the integration of state-of-the-art analysis into engineering design of load handling systems should be undertaken.

The understanding of cables is more advanced than indicated. It is necessary to continue the application and refinement of the analysis and test techniques now available which should result in progress. Ultimately, new facilities and test techniques will be needed.

Theory, characteristics, and techniques are developed in the handling of liquid, dry bulk, and containerized deployable equipment which can operate in adverse environments.

The potential tradeoffs in load handling dynamics between the equipment used and the platform should be undertaken. Large advances in capabilities may be obtained by the proper selection of equipment/ platform configuration, e.g., use of SWATH, semisubmersible, or submersible platforms instead of very large motion-compensated cranes mounted on conventional hulls.

U.S. Navy Report

Load Control A concerted effort should be made to develop the theory, techniques, and equipment necessary to permit any desired degree of load (cargo) control. Of vital importance is the ability to match load, degree of load control, support platform, and sea condition in any desired combination. Again, the three regimes to be considered should be above, below, and through the air/sea interface. The present lack of validation data is one of the major deficiencies hindering analysis and understanding of handling systems. Therefore, a considerable effort should be made to validate the theory, techniques, and design parameters and develop equipment by fabricating, instrumenting, and testing full-scale prototype handling systems. The goal for this thrust should be the fabrication of prototype systems that will routinely and successfully operate in sea state 5, moderate gale (30-knot wind speed), and 4-knot current conditions. Subsurface conditions to be met are 4-knot currents and internal wave heights of 1.2 to 2.4 meters.

Working Group Review/Workshop Comments

Load Control Emphasis should be placed on "implementation" of theory as opposed to "development" because of the basic physics theories that exist. Further emphasis needs to be placed on the validation of the basic assumptions, environmental data, and performance; an effort too often neglected.

Platform and the load handling equipment form an integral system. The size of the platform and its consequent response to seas and loads must be considered. The thrust must, therefore, include analysis of load handling missions from the standpoint of integration of platform and equipment. This implies a potential requirement for a multiplicity of systems, equipments, and platforms to perform the various load handling missions, e.g., mooring deployment, at-sea transfers, large and small object emplacement, and salvage.

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MOORINGS

U.S. Navy Report Excerpt

Scope

A. Analytics
   1. Anchor
      a. capacity
      b. sensitivity
   2. Mooring dynamics
      a. installation
      b. nonlinear drift
      c. wave slamming
      d. drag and inertia coefficients

B. Hardware
   1. Anchor
   2. Riser
      a. cable
      b. chain
      c. synthetic
      d. connectors
   3. Buoy
   4. Rigging
   5. Sensors

C. Installation
   1. Positioning
   2. Navigation
   3. Load handling
   4. Interactive analytics

Objective

Develop analytical and mechanical/design capabilities to improve the efficiency, operational life, and load capability of moorings and cable structures at all ocean depths.

Related Technologies

Related technologies are: cables; command and control; system dynamic response prediction; data transmission and handling; geotechnics; load handling; materials and structures; navigation; nondestructive testing; and sensors.

DISCUSSION OF MOORINGS

State of the Art

U.S. Navy Report

The Navy's standard mooring capability is limited to relatively protected nearshore areas. Moorings at environmentally harsh and deep water areas have been achieved, but design methodologies, equipment, installation procedures, and the success of these moorings vary considerably. Design life has been nearly impossible to predict and has varied from hours for surface moorings to years for some subsurface moorings. In nearshore areas, the offshore commercial capability is more advanced, with routine mooring installations in 100 to 200 meters of water. That capability is expanding to 500 to 600 meters. However, the offshore industry's deeper water (500 to 600 meters) moorings rely on specialized and heavy equipment which is not available for general Navy projects. High current areas and areas with hard sloping seafloors are avoided due to anchoring difficulties and uncertainties in mooring loads and motions. As water depth, severity, and complexity of environmental conditions, design life, positioning accuracy, and mooring loads increase, the capability to design and install moorings consequently decreases.

Working Group Review/Workshop Comments

The Navy report does not distinguish the two major categories of moorings, commonly identified as ship moorings and scientific or ocean-ographic moorings. The distinction goes beyond simple size. It usually is assumed that the presence of mooring lines does not significantly affect the ship's response to the seaway. Oceanographic moorings must include the dynamic mooring force in the equations of motion of surface floats. It is, therefore, useful to define the state of the art separately for these two kinds of moorings.[1-4]

The Navy has additional constraints on some moorings that are not needed for commercial moorings. For example, a deep-sea rescue operation prohibits a lengthy design, fabrication, and procurement cycle. Further, it may require compact, lightweight components that can be delivered by aircraft. Commercial moorings tend to heavy components.

The traditional design of mooring has been based on the static (catenary) equations with steady current flow, occasionally included for ship moorings and usually included for oceanographic moorings. Analytical tools (computer models) capable of predicting transient loads -- such as are imposed during installation or recovery -- and oscillating loads from wave action, and time-dependent tide and current forces are a very recent development. These programs are only beginning to reach a mature state of development. Significant generality has been attained in modeling the gross mooring geometry as a "network" of mooring elements. Modeling of rigid objects in the network, except for ships on the surface, is usually restricted to simple shapes that impose passive loads in response to the environment.

Thus, modeling oceanographic moorings containing cylindrical or spherical instrument housings is straightforward, but modeling sophisticated devices such as depth-seeking paravanes, tethered submersibles, powered bodies, and the like, is at the edge or beyond the current state of the art.

Computer models of mooring dynamics, unlike equilibrium models, usually use simple mathematical expressions for the hydrodynamic force on a cable element. The variation of force with cable attitude is over-simplified, especially in the tangential component. This is not a serious consideration in nearly vertical moorings, but the capability of modeling moorings with long, nearly horizontal elements is degraded.

The hydrodynamic characteristics of cable fairings at low Reynolds numbers are not well known, including the relation of friction drag to pressure drag in that regime. Dynamic models are rarely equipped to characterize cable fairings correctly. Some, perhaps most, dynamic models account for the elongation of line elements. Torsional and bending stiffness is treated only in specialized models.

Models in the frequency domain are relatively inexpensive to use, but they cannot model transient events. Time domain models are typically much more costly to use because the ratio of modeling time to event time is usually one or more, even when very large, fast computers are used.

With few exceptions, computer models of cable dynamics have been prepared in support of a specific ocean engineering problem. This has tended to restrict the generality of the resulting model, to give low priority to preparation of comprehensive easily applied documentation, to prevent thorough validation against experimental data, and to make little or no provision for continued model support and development once the particular hardware has been deployed.

The ability to predict vibration behavior is dependent on empirical models because there is a lack of theoretical solutions to flow-induced vibration. These models require substantial field data. As a result, the prediction of vibration response of a long flexible cylinder in a current which varies in speed and direction with depth is not possible at present with sufficient accuracy. This in turn prevents accurate estimation of drag coefficients and hence of mooring position. The suppression of flow-induced vibration is frequently attempted but not achieved, thus, considerable interest remains for both industrial and naval applications.

Nevertheless, scientific moorings in deep water are designed more or less routinely but not without specialized engineering skills. These moorings usually perform adequately within installed life of a year or more. The "edge" of the state of the art for these moorings is hardware that automatically deploys after parachute delivery from an aircraft.[5-8]

The lack of specific reliable data describing the local mooring environment is usually a significant weak link in mooring design. Often the characteristics of some of the mooring components are inadequately understood.

The state of the art does not identify geographic limitations on mooring feasibility. For example, current technology is unable to design moorings in which ice loads may occur. The tacit assumption is: open ocean mooring. Surface and near-surface moorings in high current areas are not reliable at the present time.

The sources of outside technology input to the Navy are not stated specifically; the oil industry is usually implied. Other sources include:

- Universities and institutions;
- R&D corporations (e.g., Hydronautics, Lockheed, Westinghouse, General Electric, EG&G, Inc.);
- The potential ocean mining industry;
- The potential ocean thermal energy conversion (OTEC) industry;
- Foreign corporations (North Sea oil companies, e.g., British Petroleum, and Royal Dutch Shell);
- Wire and synthetic rope manufacturers (e.g., U.S. Steel, Emerson and Cummings, Samson, Wall Rope, Rochester Cable, and Dupont Kevlar Special Products Group).

Forecast

U.S. Navy Report

The Navy's understanding of the dynamics of moored systems, the design and behavior of anchor systems, open-ocean load handling systems, deeper water installation methods, and buoy systems is expanding under the Navy's exploratory development program. The offshore industry's experience with platform moorings also is increasing. Commercial data is often proprietary, however, some data does become available for general use. A concerted effort is required to consolidate and build upon this technological base, with an overall intent of reducing the vast uncertainties and relatively high costs associated with short- and long-term moorings, and ocean cable structures. Without such a concerted effort, the Navy's ability to design, install, operate, and maintain moorings and cable structures at all ocean depths will not improve substantially in the foreseeable future.

Working Group Review/Workshop Comments

Two additional potential sources for ocean mooring technology are OTEC and the ocean floor mining industries which may develop.

Commercial mooring design and practice will advance, but it is unlikely to contribute to any special Navy needs for lightweight moorings that can be designed and deployed quickly.

The introduction of new materials that advance mooring technology is an imponderable. These materials, in the past, have not been developed for the mooring industry but have been recognized and adapted to mooring applications. Perhaps emphasis should be placed on the fact that reduction in size and weight of the connecting lines and components between the ship or buoy and the bottom depends upon the development of higher strength materials compatible with the marine environment. It is expected that the need to implant reliable moorings in deeper water and in rapid surface currents will continue, and hence, the motivation to search for better materials will continue.

Proposed Thrusts

U.S. Navy Report

Mooring Analytics The analytical methods presently available to predict the holding capacity of anchors and the dynamic response of moorings and cable structures do not permit their confident design. A concerted effort should be directed at finalizing and validating holding capacity prediction schemes for conventional anchors in a broad range of sediment seafloors and for propellant embedded anchors in rock seafloors. In addition, existing analytical methods for evaluating mooring dynamics need to be simplified and updated to include installation dynamics, nonlinear slowly varying drift forces, and effects of wave slamming, and improved values for drag and inertia coefficients for vessels in high sea states and currents. This thrust would greatly enhance the Navy's ability to design, install, and use successfully moorings and cable structures in all ocean depths at minimum costs. When the necessary development is completed, the technology should be validated through design, installation, and monitoring of a deep ocean mooring.

Working Group Review/Workshop Comments

Mooring Analytics Confidence in mooring design requires some distinction between total system dynamics and mooring line dynamics. The latter is well modeled in SNAPLD and SEADYN, for example. Considerable modeling improvement is required, however, to better represent the moored ship and mooring cable(s) interface and the cable to anchor interface.

A thrust is necessary to validate models and associated parameters by experimentation to determine such characteristics as hydrodynamic resistance, mass coefficients, and others. Anchor holding power is very important and relates with the sea bottom geotechnics field of endeavor.

A thrust is necessary in computer model simplification, and a note is made in the system dynamic response prediction section to this regard. The user's point of view should be emphasized. For example, he should be able to input his cable description and expect that the program could supply or calculate the corresponding drag and added mass coefficients with the help of subroutines established for that purpose. Nonetheless, it is understood that computer models are costly to prepare because of the variety of sophisticated technical skills required. Some formidable examples are in dynamic fluid flow, nonlinear mathematics, and advanced numerical techniques. Most ocean engineering projects must either adapt their problem to the limitations of an existing model or, the more typical recourse, do without. There is much need for on-going support of the modeling effort per se, i.e., not linked to specific hardware programs. There is a concomitant need for a compendium of models, revised at appropriate intervals, to which users could refer. The most recent such document is a decade old.[2]

There is need for an additional thrust for practical, useful, "engineering type" models of current profiles for mooring designs. The model(s) should combine the following effects: wind induced, geostrophic, inertial, tidal, topographic, and eddy dominated. The data should be compiled for ocean basins or well-studied areas such as the Gulf Stream, Kuroshio, Somalia, and others.

Statistical approaches for determining long-term loads on, and the responses of, mooring cables should include the development of environmentally dependent nonlinear transfer functions. Models incorporating these nondeterministic tools could provide rapid, computationally efficient methods for assessing natural excitation-coupled surface platform and mooring effects on the mooring cables.

U.S. Navy Report

Longevity of Mooring Components A strong effort ought to be undertaken to improve the Navy's ability to predict and extend the service life of moorings and cable structures. The thrust here is to use experience, appropriate analytical techniques (e.g., finite element analysis, and dynamics analysis) and tests to determine why and how commonly used mooring/cable system components (e.g., anchors, cables, chains, lines, and connectors) fail prematurely in service. This insight would then be used to improve the reliability and life of the components through changes in component material, configuration modifications or redesign, or by elimination of the condition causing the failure.

Working Group Review/Workshop Comments

Emphasis should be placed on a thrust toward environmental testing that provides the most valuable data return at least cost for systematic exposure of mooring components in controlled sea tests. Samples could be loaded at different percentages of their strength to correlate longevity with stress levels and, thus, establish and demonstrate safety factors, information which is greatly needed for engineering design criteria. As an example, preliminary evidence indicates that synthetic fiber moorings are subject to both chemical and biological degradation in service.* Specifically, certain communities of microorganisms establish themselves among the innermost strands of synthetic fiber causing mechanical and chemical effects that accelerate failure. To carry out reliable design testing, it will be necessary to test either in situ or simulate the complete biological and chemical conditions of the site.[9]

Given such testing as suggested, there is no naval center for the collection of mooring experience. The Navy's proposed thrust toward mooring technology integration should include provision for a common library of validation data.

U.S. Navy Report

Mooring and Cable Structure Installation A concerted effort should be undertaken to develop and integrate the technologies which support reliable installation of moorings and cable structures at all ocean depths. The technologies center on the equipment needed to transport and handle the structural hardware of the mooring cable system (e.g., vessels, winches, and cranes); the sensor systems on the mooring or structure (e.g., tensionmeters, accelerometers, and position sensing devices) that provide real-time data on its location, status, for example; and the analytical hardware and software (i.e., onboard

*John Lindberg presentation to the Marine Board at San Diego, California, June 3, 1982.

interactive analytical capability) that can be used onsite to adjust the position, orientation, or status of the components during the installation. Integration of these technologies, perhaps by coupling the handling equiment to the sensor and analytical systems, will greatly improve the speed, precision, and safety of mooring and cable structure installations.

Working Group Review/Workshop Comments

The integrated thrust described in the Navy report is appropriate. It would be constructive to indicate the complexity of the moor, e.g., 4-point moor for a supply vessel. While the emphasis on equipment, sensors, and analytical hardware and software is correct strategy, other planning factors for successful complex mooring installations should include:

- Site survey;
- Site preparation, e.g., surface and bottom markers;
- Deployment scenario;
- Logistics;
- Communciations;
- Weather limits;
- Contingency plans;
- Personnel training.

In addition there should be application of dynamic analytical modeling to the real-time installation and subsequent operation for the purpose of proper control of the moorings.

Mooring Component Development Component development should be emphasized in future thrusts and is noted in the following comments but was not specifically identified in the Navy report.

Mooring in some ocean environments is not feasible now but is needed, e.g., rapid currents in deep water as in the Gulf Stream. Use of streamlined fairings to reduce the drag of mooring lines has often been proposed which would permit mooring in high currents. They would also help achieve more verticality which is desired (approximately 1 degree for some vertical acoustic arrays in milder currents). However, the efficiency of fairings (i.e., hard plastic) is yet to be established under conditions of deep water with time-varying currents and long lengths (kilometers).

The holding power of conventional anchors in deep ocean basins (5,000 meters typical) is not well known. Furthermore, in most instances, conventional anchors cannot be used because the mooring line pulls at large angles from the horizontal. Anchors should be designed and test specifically for deep-sea mooring applications.

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APPENDIX A

REVIEW AND WORKING GROUP PARTICIPANTS

The following persons listed below participated in the various working group reviews and in the workshop. Those who did not participate in the workshop are noted by (1), those who participated in the workshop only by (2), and members of the panel by an asterisk(*).

Energy Systems - (Review meeting held April 26-27, 1982, Sunnyvale, California.)

James G. Wenzel* - (working group leader) Lockheed Missiles and Space Company, Inc.
Alfred A. Bove - Mayo Clinic
John E. Brophy[1] - Lockheed Missiles and Space Company, Inc.
A. Douglas Carmichael - Massachusetts Institute of Technology
Benjamin Gitlow - United Technology Corportion (retired)
Kenneth L. Krug[1] - Lockheed Missiles and Space Company, Inc.
Yi Sheng Li - Lockheed Missiles and Space Company, Inc.
Ernest L. Littauer - Lockheed Missiles and Space Company, Inc.
John Louzader[1] - Lockheed Missiles and Space Company, Inc.
Enrico W. Petrocelli[1] - University of Rhode Island
Willard F. Searle[2] - Searle Consortium (also participated in dynamics group for moorings during workshop)
William Whitmore[2] - Lockheed Missiles and Space Company, Inc. (served as working group rapporteur during workshop)

Materials and Testing - (Two review meetings were held: one covering materials and structures and nondestructive testing on August 16, 1982, in Washington, D.C., and the other on geotechnics on August 20, 1982, in Houston, Texas.)

H. Ray Brannon*[1] - (working group leader during meetings) Exxon Production Research
John W. Coltman* - (working group leader during workshop) Westinghouse Electric Corporation
James H. Bechtold - Westinghouse Electric Corporation (participated in working group meetings as noted)

Michael J. Buckley - Rockwell International
Joseph E. Burke - General Electric (retired)
Ronald Eby[1] - Bureau of Standards
J. D. Murff - Exxon Production Research
John A. Focht[1] - McClelland Engineers, Inc.
Wayne W. Ingram[1] - Law Engineering Testing Company
Bramlette McClelland[2] - McClelland Engineers, Inc.
William H. Hartt[2] - Florida Atlantic University
Richard Ikeda[2] - E. I. du Pont de Nemours and Company
Paul G. Riewald[2] - E. I. du Pont de Nemours and Company
Richard W. Rumke[2] - staff officer, Marine Board
(rapporteur during workshop)

Data Systems - (Review meeting held May 18, 1982, Washington, D.C.)

R. Frank Busby, Jr.* - (working group leader) Busby Associates, Inc.
Arthur B. Baggeroer - Massachusetts Institute of Technology
Robert D. Ballard[1] - Woods Hole Oceanographic Institution
John W. Coltman* - Westinghouse Electric Corporation
Walter E. Gray[1] - Diverless Systems, Inc.
Richard Hoglund[1] - ORI, Inc.
Wayne L. Kerr[1]- Wayne Kerr and Associates
William H. Marquet - Woods Hole Oceanographic Institution
Geoffrey K. Morrison[2] - Neil Brown Instruments Systems
J. Edward Snyder[2] - Consultant
Denzil C. Pauli[2] - Consultant to Marine Board
(rapporteur during workshop)

Control - (Meeting held July 15, 1982, Cambridge, Massachusetts)

Ira Dyer* - (working group leader) Massachusetts Institute of Technology
Brian L. Cuevas - Charles Stark Draper Laboratories
Edward C. Brainard - ENDECO, Inc.
Richard Hoglund[1] - ORI, Inc. (also served in review of data-systems working group)
Thomas Sheridan[1] - Massachusetts Institute of Technology
Robert C. Spindel[1] - Woods Hole Oceanographic Institution
Francis J. M. Sullivan[2] - Bolt, Beranek, and Newman, Inc.

Dynamics - (Meeting held June 4, 1982, Washington, D.C.)

Marshall P. Tulin*[1] - (working group leader) University of California, Santa Barbara
Henri Berteaux - Woods Hole Oceanographic Institution
Robert G. Dean[1] - University of Florida
James Duncan - Hydronautics, Inc.
Shelton Gay - MAR Associates, Inc.
William S. Gaither[2] - University of Delaware

Eugene Miller - Hydronautics, Inc. (served as coordinator during workshop)
J. Kim Vandiver - Massachusetts Institute of Technology
D. K. Ela - Consultant to Marine Board (rapporteur during workshop)

Corresponding Participants:

Ronald L. Geer - Shell Oil Company (panel member)
Ben C. Gerwick, Jr. - University of California, Berkeley (panel member)
Christian Lambertsen - University of Pennsylvania (energy systems working group)

APPENDIX A-1

NAVY PARTICIPANTS IN WORKING GROUP REVIEWS AND WORKSHOP

The following persons, both civilian and military, participated in working group reviews and in the discussions during the workshop assessment sessions. These discussions between panel members, invited experts, and Navy participants have been helpful in understanding the Navy's needs and objectives in deep ocean technology development. The panel particularly appreciates the assistance of the Navy participants listed below. The code number beside each person's name refers to the meeting(s) and workshop identified at the end of this portion of the appendix.

Norman D. Albertsen, NCEL
(4, 5, 8, 9)
Perry B. Alers, NRL
(1, 3, 4, 5, 9)
Frank Armogida, NOSC
(3, 9)
Richard L. Bloomquist, DTNSRDC
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Earl Carey, NRL
(4, 6)
Joseph Cavallaro, DTNSRDC
(7, 9)
Robert J. Chomo, DTNSRDC
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R. N. Cordy, NCEL
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Philip J. Dudt, DTNSRDC
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J. H. Elkins, NORDA
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Norman Estabrook, NOSC
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Elzie Freeman, NCSC
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John Freund, NAVSEA, Research and Technology Office
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Albert Himy, NAVSEA
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Terry Hoffman, NOSC
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John H. Howland, Captain USN,
Office of the Chief of Naval Operations
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Herbert A. Johnson, NRL
(1, 2, 3, 4, 5, 6, 9)
James Katayama, NOSC
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Martin A Krenzke, DTNSRDC
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Chester D. Ozimina, NRL
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Robert Peloquin, NAVFAC
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Andreas Rechnitzer,
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(9)
Eugene A. Silva, ONR,
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David C. Smith, NOSC
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Richard C. Swenson, NORDA
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Howard Talkington, NOSC
(5, 9)
Dale G. Uhler, NAVSEA
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George H. Verd, Captain USN,
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George A. Wacker, DTNSRDC
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Robert Wernli, NOSC
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Irvin Wolock, NRL,
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Designations for Navy Facilities/Locations

DTNSRDC - David Taylor Naval Ship R&D Center, Annapolis, MD 21402

NAVSEA - Naval Sea Systems Command, Washington, D.C.

NAVFAC - Naval Facilities Engineering Command, 200 Stovall Street Alexandria, VA 22332

NCEL - Naval Civil Engineering Laboratory, Port Hueneme, CA

NCSC - Naval Coastal Systems Center, Panama City, FL 32407

NORDA - Naval Ocean Research and Development Activity, NSTL, Bay St. Louis, MS 39529

NOSC - Naval Ocean Systems Center, San Diego, CA 92152

NRL - Naval Research Laboratory, Washington, D.C. 20375

Meetings and Workshop for Panel and Working Groups

1. Panel Meeting, January 28-29, 1982, Washington, D.C.
2. "Energy Systems" Working Group Meeting, April 26-27, 1982 Sunnyvale, CA
3. "Data Systems" Working Group Meeting, May 18, 1982, Washington, D.C.
4. "Dynamics" Working Group Meeting, June 4, 1982, Washington, D.C.
5. Panel Meeting, June 25, 1982, Naval Ocean Systems Center, San Diego, CA
6. "Control" Working Group Meeting, July 15, 1982, Cambridge, MA.
7. "Materials and Testing" Working Group - materials and NDT meeting August 16, 1982, Washington, D.C.
8. "Materials and Testing" Working Group - geotechnics meeting August 20, 1982, Houston, TX
9. Workshop, September 23-24, 1982, Washington, D.C.

APPENDIX B

RESEARCH REQUIREMENTS FOR IMPROVED EFFECTIVENESS AND SAFETY IN DIVING OPRATIONS*

Relation to Support of Navy
Technical, Salvage, and Rescue
Diving Operations

L-II

Institute for Environmental Medicine
University of Pennsylvania
August 1982

Adapted by C. J. Lambertsen and A. A. Bove
from 1982 University/Industry Appraisal of Status
of Research Requirements for Advance of
Manned Undersea Activity

*FOR USE BY WORKING GROUP ON ENERGY SYSTEMS-LIFE SUPPORT SYSTEMS, MARINE BOARD, NRC, COMMITTEE ON CIVIL/NAVY OCEAN ENGINEERING

RESEARCH REQUIREMENTS FOR IMPROVED EFFECTIVENESS AND SAFETY IN DIVING OPERATIONS

Relation to Support of Navy Tactical, Salvage, and Rescue Diving Operations

Table of Contents

Introduction

Two major objectives continue to guide the stages of basic biomedical research, the practical applications of human physiological research, and the engineering developments which together have provided for direct manned undersea support of Navy diving and salvage operations, submarine rescue, and special tactical diving needs. These related objectives are as follows:

1. To increase the scope and effectiveness of work performance by individual divers in the alien undersea environment.

2. To assure safety during diving exposure, thereby providing protection of the diver and maintenance of his capacity for effective undersea operations of all types.

Such goals have been contributed to extensively over past years by Navy-supported research, the majority of which has been done in nonmilitary laboratories working under Navy contract. Both in basic research and in operational evaluations, these gains have been attained by a series of stepwise approaches to practical limits of tolerance. Requirements and opportunities now exist for further improvement in the important shallow and moderate diving depths, as well as for attempts to define the physiologically practical limits of diving depth and duration for Naval operations.

Significant Advances

The present ability to apply a clear mind, sharp senses, communication of observations, a dextrous hand, and physical force has derived from any specific physiological research, engineering, and operational contributions. Application of these extensive advances is not complete, research is not complete, and the advances have in the normal way opened up new opportunities for useful extension of undersea work.

Specific advances, by civilian and naval groups, of exceptional importance to diving applications have included the following:

- The concept and development of saturation diving.
- Development of the submersible decompression chamber and the deck decompression chamber for improved safety and capability in prolonged undersea operations.
- Demonstration of diver lock-out from submersibles.
- Determination of pulmonary oxygen tolerance limits.
- Determination that helium does not suppress mental or sensory function at extreme pressures.
- Improvement in decompression through use of sequential administration of selected inert gases and oxygen.
- Development of thermal protection, and recognition of serious respiratory heat loss in deep water.
- Development of hyperbaric oxygen therapy for decompression sickness and gas embolism.
- Improved methods of treating decompression sickness by use of drugs and other agents as adjuncts to decompression and oxygen.
- Discovery and prevention of isobaric inert gas counter-diffusion gas lesion diseases.
- Identification of compression-induced neurological derangements.
- Development of saturation-excursion diving procedures.
- Demonstration of practical underwater working capability to 1,600 feet.
- The reconstruction of intelligible voice communication during helium breathing at high pressure.

These and extensive other research applications or developments responsible for current undersea operating capabilty have involved many hundred of man years and many millions of dollars of laboratory research and development in undersea biomedical laboratories. <u>Much such laboratory work in the past has been in sensible anticipation of new Navy diving requirements, rather than in direct response only to officially stated operational need</u>.

In the present circumstances of accelerated military and industrial application of past research, it is necessary to consolidate existing research gains and direct future research activity towards meeting forseeable requirements not yet realized.

The understanding and overcoming of present limitations will continue to involve basic and applied biomedical research, engineering, and operational development, and extensive communication among these related activities. It will require the fullest collaboration and investment by qualified naval and civilian laboratories.

Scope of Physiological Research Requirements

Clearly there is no practical working circumstance involving a more severe and complex composite of physiological stresses than is encountered in modern diving. The Olympic athlete functions to physical exhaustion but in an ideal and harmless environment. The astronaut is essentially unstressed, even on the atmosphere-less lunar surface, protected by engineering from most environmental hazards and even need for severe exertion.

For the human diver, each of many discrete environmental forces increases with the greater hydrostatic and gas pressures of diving, and some also increase with the duration of exposure. He is the only worker who becomes "physiologically trapped" by the high pressure environment and is unable to leave it at will. It still requires longer to decompress to sea level from a helium saturation exposure at the edge of the continental shelf than to return to earth from a landing on the moon.

Pertinence of Environmental Stresses to Navy Diving Operations

In the summary outline following, major factors normally simultaneously encountered in the diver's working environment are isolated in order to identify them. In the face of these factors, physiological limits of many forms do exist for diving, in spite of our eminent recent successes in extending practical undersea working support of the military diver. <u>Limits exist at all depths from the shallowest to deep diving</u>. Some can be eliminated by engineering. Some can be tolerated. Some can be masked. Most persist and re-emerge with increasing depths and durations of diving. They are included below under 10 broad topics, as follows:

- o Thermal effects;
- o Oxygen poisoning;
- o Decompression related illnesses;

- o Isobaric counterdiffusion effects;
- o Respiratory effects of increased gas density;
- o Narcosis by inert gases;
- o Neurological disruption by hydrostatic pressure;
- o Speech decrement;
- o Toxicity from atmospheric and water-borne contaminants;
- o Preventative hygiene in closed hyperbaric systems.

While the above listing presents separated factors, in reality they must be considered as intimately interacting during work at high pressure in a complex physiological interplay of functions and effects. Normal adaptability serves to compensate for many potentially limiting effects. Others are overcome by applied physiological or by engineering adjustment.

Selected samples of specific influences induced by each of these factors include:

Specific Influences

Thermal Effects - Excessive Body Cooling or Heating

Hypothermia

- o Loss of body heat through skin to cold water or gas environment at all depths.

- o Exaggerated body heat loss via respiratory gases (helium) at increasing depths.

- o Progressive decrement in mental, sensory, psychomotor and physical competence. Interaction with narcotic effects of gases. Respiratory/circulatory failure and death.

Hyperthermia

- o Progressive rise in body temperature in uncontrolled, hot, high-pressure gas environment. Failure of mental and physical function. Lethal.

Oxygen Effects - Beneficial and Toxic Actions

Physiological

- o Undesirable suppression of respiration by oxygen. Limits of pulmonary oxygen diffusion at extreme depths (pressures). Maintenance of tissue viability in gas lesion diseases.

Toxic

o Specific chemical toxic effects of oxygen upon cell and organ functions (e.g., brain, eye, lung, blood)

Physical

o Facilitation of inert gas elimination and bubble resolution in decompression sickness. Improved decompression schedules for deep and shallow exposures. Prevention of decompression and isobaric gas lesion diseases. Increase in reliability of therapy in decompression sickness and other gas lesion diseases.

Decompression and Isobaric Counterdiffusion Gas Lesion Diseases - Prevention and Treatment

Facilitation of decompression and prevention of decompression sickness

o By maximal use of oxygen, effective inert gas sequencing, influence of thermal factors, and drugs.

Therapy of gas lesion diseases (decompression sickness, isobaric gas lesion diseases, gas embolism)

o By maximal use of oxygen, effective inert gas sequencing, influence of thermal factors and drugs.

Respiratory Gas Density Effects (Respiratory Exhaustion Due to High Gas Density)

Respiratory resistance (at Work and at Rest)

o Relation to physical work capacity at shallow and increasing depths.

o Interference with oxygen uptake and carbon dioxide elimination.

o Interaction with mental depression of narcosis and hypothermia.

o Projected respiratory failure in prolonged exposure at extreme depth.

Gas Narcosis (Decrement in Mental, Sensory, Psychomotor, and Physical Competence)

- Relation to composite effects of nitrogen, carbon dioxide, oxygen, and low temperature in shallow diving. Relation to inert gas mixtures and respiratory resistance in shallow and deep diving.

Voice Decrement (Decreased Capability for Communication of Intelligence and Information)

- Physical influences of helium and gas density upon vocalization. Physiologic and electronic restoration of voice communication at high pressures.

Hydrostatic Pressure Effects (Neurological, Neuromuscular Dysfunctions at High Ambient Pressures)

- Influences of rates and degrees of compression, limits of tolerance, rates of physiological adaptation, modification by gases and drugs, reversible and residual effects.

Environmental Toxicity

- Detection and effects of toxic atmospheric contaminants in high-pressure breathing gases and closed compartment atmospheres.

- Detection and effects of water borne chemical intoxicants, radiation hazards, energy field hazards (e.g., acoustic, electrical).

Infection Prevention (Relation to Prolonged Work and Residence in Closed Compartment, Wet, Crowded, High-Pressure Atmospheres)

- Relation to advances in submarine environmental hygiene and infectious disease prevention.

Relation to Practical Undersea Operations and Support of Navy Diving Activities

The aggregate body of environmental factors and physiological constraints, cited earlier, can be allocated to three necessarily related topics pertinent to success in practical diving and undersea operations, namely:

I. Work Effectiveness

- Improvement in response, technical precision, communication, mental competence, manual performance, physical capacity, endurance.

- Influence upon operations planning, down time, error, reliability, and cost effectiveness of manned versus completely unmanned systems.

II. Work Safety

- Ensurance of personal safety, to meet moral obligations, reduce error, increase work effectiveness, avoid costly delays in diving operations due to accident or environmental injury, reduce the cost of expensive engineering systems.

III. Treatment Functions (Improvement in Specialized Treatment of Illness or Accidents in Diving or at High Pressure)

- Decompression incidents, hypothermia, infection, trauma, and toxic effects. Reduction of disabling or chronic injury. Reduction of down time required by therapy of accident.

Based on the above considerations, it is evident that both basic and applied research are highly necessary, not specifically to explore extreme depths and durations, but for the overall range of diving conditions now in common use, to improve:

- Reliability of decompression.
- Efficiency of routine and special operations.
- Effectiveness of the individual in the water column from shallow to deep depths.
- Personal safety.

Overlap of Operations and Research Areas

Ten major environmental factors exert overlapping influences in relation to the three operational areas as follows:

I. Work Effectiveness

- Thermal effects
- Oxygen effects
- Decompression and isobaric counterdiffusion
- Respiratory gas density effects
- Gas narcosis
- Voice decrement
- Hydrostatic pressure effects

II. Work Safety

- o Dempression and isobaric counterdiffusion
- o Oxygen effects
- o Gas narcosis
- o Hydrostatic pressure effects
- o Environmental toxicity
- o Infection prevention
- o Voice decrement
- o Respiratory gas density effects

III. Treatment Functions

- o Thermal effects
- o Decompression and isobaric counterdiffusion effects
- o Oxygen effects
- o Therapeutic gas mixtures
- o Toxicological effects
- o Infection
- o Trauma*
- o Chronic, residual effects*

* Ancillary considerations

This inevitable overlap results in multiple useful applications of research results obtained in carefully planned investigations.

Biomedical and Life Support Research and Development Required to Support Manned Undersea Operations

While the purpose and operational methods for diving vary between Navy and Industry, the diver and the specific stresses are the same. Research requirements therefore overlap nearly completely, and information obtained is mutually advantageous. Military, university, and industrial research and development efforts are complementary and necessary, with no one able to match fully the contributions of the other. Without full collaboration, further real progress is unlikely.

Over recent years, university and Navy laboratories have both together spearheaded basic and applied research aimed at opening new opportunities for advance. Navy laboratories participate to a limited degree in basic studies and contribute most heavily in development and validation of operating capability. University laboratories have carried on the most extensive life sciences research support functions.

At present, industrial organizations perform or support essentially no diving research but rapidly utilize the extensive contributions of university and Navy laboratories. Industry, uninhibited by absence of official "operational requirements," responds to "operational opportunity" and has carried deep diving technology beyond naval operating status.

The summary following outlines projected research needs and proposed Navy thrusts for consolidation of gains in salvage diving, improvements in operating capability by special naval diver groups, prevention of harm or functional limitation, and improvement in therapy of diving-related accident.

A. Needs Concerning Thermal Effects

- Improved heating systems for tethered diver, divers in vehicles, and free divers.
- Improved understanding of human physiologic responses to cold exposure and heat stress in underwater and hyperbaric environments with variable inert gases.
- Combined influences upon mental performance of hypothermia, nitrogen narcosis, and hyperoxia.

B. Needs Concerning Oxygen Effects and Oxygen Tolerance

- Fundamental definition of oxygen poisoning effects upon neural structures (membranes, synaptic function, sensory structures).
- Effects of hyperoxia on central nervous system and other vital organ systems (in addition to lungs). Development of oxygen tolerance curves for vital organs and functions in man.
- Identification of early CNS and pulmonary oxygen toxicity.
- Extension of oxygen tolerance over full range of useful O_2 pressures (to increase capability of diving, decompression, and therapy of decompression sickness).

C. Needs Concerning Decompression Related Illness

- Improved understanding of bubble growth and formation in the body.
- Improved understanding of bubble effects on body fluids, tissues, organs, and systems.

- o Improvement of safety and efficiency of decompression in:

  - Prolonged air diving with staged decompression and with surface decompression with oxygen.

  - Deep helium/oxygen diving with staged decompression and with surface decompression with oxygen.

- o Optimization of oxygen use in diving and decompression (relation to inert gas elimination and oxygen toxicity of organ systems).

- o Development of multiple gas decompression schedules.

- o Improvement in nitrogen/oxygen saturation-excursion diving and decompression schedules.

- o Improvements in therapy of gas lesion desease (decompression sickness occurring at high pressure, or not overcome by standard oxygen therapy methods, mixed decompression and isobaric gas lesion diseases).

D. Needs Concerning Respiratory Effects of Increased Gas Density

- o Definition of physiologic limits to work imposed by increased breathing gas density, and means of avoiding respiratory limitations in deep diving.

- o Diving respiratory systems designed to eliminate respiratory insufficiency at deep depths.

- o Tolerance to prolonged (multiday) exposure to high respiratory gas density in shallow and deep diving.

E. Needs Concerning Undesirable Effects of High Pressure and Inert Gas

- o Improved understanding of combined pressure and inert gas narcotic interaction on CNS function and on other organs and tissues.

- o Improved understanding of hydrostatic pressure effects of organs and tissues.

F. Needs Concerning Environmental and Atmospheric Toxicity and Preventative Hygiene

- o Review of toxic chemicals with potential for breathing gas, atmospheric or water contamination in Navy diving operations.

- Evaluation of changes in known chemical toxicity induced by the hyperbaric environment.

- Development of operational procedures for prevention of toxic injury to Navy divers.

- Evaluation of potential radiation hazards in peacetime and wartime diving operations.

- Detection of and protection from in-water energy fields from acoustic, electric, or magnetic radiation.

- Identification of major pathologenic microbiological contaminants of equipment and chambers used in undersea work.

- Development of operational procedures to protect divers from pathogenic microorganisms in diving operations.

- Determination of residual or long-term effects of physical and chemical toxic exposure in man.

G. Needs Concerning Speech Development

- Elaboration of basic voice decrements with gas mixtures at increased pressure.

- Reliable voice encoder/decoder which operates automatically with all depths and gas mixtures.

H. Needs Concerning Interactions

- Determination of adverse interactions of environmental and physiologic stresses such as temperature, pressure, inert gas narcosis, inert gas exchange (decompression, isobaric counterdiffusion), oxygen partial pressure, and exercise.

- Determination of limiting effects upon human sensory, mental, psychomotor, respiratory and physical performance of:

  - Work at increased ambient pressure.
  - Oxygen at increased pressure.
  - Hypothermia, inert gas, and combined effects of the above.

- Methods of early detection of adverse response to the combined physiologic-environmental stresses encountered in the undersea environment.

APPENDIX C

LOAD HANDLING BIBLIOGRAPHY

The following bibliography was compiled by Shelton Gay, MAR Associates, who was a member of the working group on dynamics.

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER	2. GOVT ACCESSION NO. 3 [illegible] 751
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) NAVY LONG-RANGE DEEP OCEAN TECHNOLOGY: AN ASSESSMENT OF CURRENT DEVELOPMENT, FORECASTS, AND RESEARCH THRUSTS	5. TYPE OF REPORT & PERIOD COVERED Proceedings of a Workshop
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Panel on Civil/Navy Ocean Engineering Ira Dyer, Chairman	8. CONTRACT OR GRANT NUMBER(s) N00014-82-C-0032
9. PERFORMING ORGANIZATION NAME AND ADDRESS Marine Board National Research Council Washington, D.C. 20418	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Department of the Navy Arlington, Virginia 22217	12. REPORT DATE
	13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution of this report is unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Financial support provided by the Departments of Interior, Commerce, State and Energy, U.S. Coast Guard, Navy, Army Corps of Engineers, and National Science Foundation in the form of a general support grant administered through the Office of Naval Research.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Energy Systems and Conversion
Life Support
Propulsion and Auxiliary Machinery
Materials and Structures
Nondestructive Testing
Geotechnics
Sensors
System Dynamic Response Prediction
Data Transmission and Handling
Moorings
Cables
Load Handling
Robotics, Teleoperators, and Work Systems
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Navigation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The proceedings emcompass a workshop held September 23-24, 1982, review of the state-of-the-art, forecast and research ~~thrusts in~~ the above technology areas (see key words) which were evaluated by the Navy in its report, U.S. Navy Long-Range Deep Ocean Technology Evaluation (1982).

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