Apr 1st, 8:00 AM

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IMPACT OF AEROSPACE TECHNOLOGY
ON FUTURE OCEAN SYSTEMS

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INTRODUCTION

The ocean, like space, is a rather hostile environment for different reasons; constraints of extreme pressure with depth, poor visibility and highly corrosive properties. Although submersibles have operated in this medium since the turn of the century, they have been operational essentially in the same limited plane as a surface vessel and use the ocean primarily as a covert cloak. Mission flexibility in using the third dimension (depth) has been constrained by stringent structural requirements. This presentation will discuss technological advancements required to make significant contributions to future ocean oriented commercial and military systems. There is not a direct trans­fusion of technology from outer to inner space but there are key areas where specific aerospace technology spin-off derivatives have merit. These will be addressed.

THE ENVIRONMENT

To put things in perspective, let's quickly review the operating environment for inner space systems—first, a rough rule of thumb is that salt water is 800 times more dense a medium to work in than air.

Second, sound propagation characteristics in water are an important factor in submersible operations because of their navigational and vehicle detection attributes. Since water absorbs far less energy than air, it is a much better conductor of sound. This characteristic has been used to maximum advantage in current sonar equipment. Such equipment is used for determining distance and direction by measuring an echo return from a given directional signal, very comparable to radar.

Third, the velocity of sound in sea water is a function of temperature, salinity, and the changes in pressure associated with changes in depth. Remember that an increase in any of these factors tends to increase the velocity. Sound is propagated at a speed of 4,945 f.p.s. for 60°F at one atmosphere. Underwater sound transmission is degraded considerably by refraction, attenuation and limitations of spectral range, making communication difficult, specifically when multipaths and reverberations occur.

Fourth, underwater vision is severely hampered by the absorption and scattering of light, further compounded by backscatter from particulate matter suspended in the water.

Fifth, surface and sub-surface ice in our polar regions impede operational flexibility.

Sixth, salt water corrosion and marine fouling are ever present omnipotent factors in survivability and operability of ocean-going systems.

Seventh, the major environmental factor to contend with is pressure as it increases rapidly with depth increase at a constraining rate of approximately 50%; for example, 4,450 psi at 10,000 feet depth. This has a major impact on submersible design due primarily to pressure hull structural weight increases.

With these major constraints firmly in mind, let's look at our present status and where technology advancements are sorely needed to cope with this hostile environment.

TECHNOLOGY ADVANCEMENTS

The National Commission on Marine Science, Engineering and Resources summarized our current ocean technology position quite well (1). "The key to the study of the deep ocean lies in the ability to deploy present technological capabilities effectively and to focus on a number of critical technological developments which will provide the capability to do in the future what cannot be done today. It is the view of the Commission that there is no single device or system, manned or unmanned, that can do the job. What is needed is a selected mix of technological systems that will give the nation the necessary capability. Among these are man-in-the-sea techniques, manned submersibles, and unmanned instrumentation systems."

The Commission's recommendations were more specifically addressed by Vice President Agnew when he outlined six program areas for consideration by agencies for their FY 1971 programs. One of these is "initiate a long range Federal contract program..."
in basic marine technology so as to develop the capability to work in the entire marine environment." This is a tall order, or maybe I should say "deep"!

What are some of these critical technologies?

Pressure Hull

The present nuclear powered combat submarines can operate only in relatively shallow depths as compared to the new breed of deep diving submersibles. The latter, like spacecraft, must be designed for minimum weight for a specified operating condition.

The reason for the present two dimensional rather than three dimensional capability can best be shown by taking a closer look at the design requirements dictated by the operating environment. This is typified as shown in Figure 1. Note the penalties associated with operating at greater depths. Particularly, how the environmental pressure at operating depth impacts severely on payload capability and structural requirements (2). For example, during the design of our research submersible, DEEP QUEST (Figure 2), steel appeared to be the only satisfactory material available at a reasonable price for immediate use for a man-rated pressure hull. Commonly used HY-80 and HY-100 steels represented too great a weight penalty for the strength required (80 ksi yield). In addition, there was no realistic producibility experience for heat treatable steels above 100 ksi yield. However, aerospace technology proved to be the answer. The Air Force was just completing their 260-inch rocket case program utilizing an 18% nickel maraging steel which in the 200 ksi yield range indicated excellent mechanical properties for a deep operating submersible. Its welding and general fabricability properties were known. In addition, at the 200 ksi yield strength level, the material had excellent potential because of a lower pressure hull weight-to-displacement ratio. Therefore, after slight modifications to the Air Force chemistry to improve fracture toughness, a 200 ksi yield maraging steel was selected for DEEP QUEST. This permits an operational depth of 8,000 feet and a collapse depth in excess of 12,000 feet with a pressure hull thickness of .895 of an inch.

As a result of the stringent constraints placed on vehicle payload and structure when operating in the deep ocean, all such submersibles are characterized by low design speeds and low hydrodynamic drag to reduce propulsion power requirements and provide longer mission duration. This technological problem is somewhat analogous to that faced in aircraft design in optimizing vehicle performance to meet a high altitude mission requirement.

The designers of future generation deep submersibles will no doubt take advantage of aerospace structural design techniques including computer-aided design. Sought after materials will be new high strength-to-weight HY 180-210 steels and transging titanium alloys of 160-180 ksi yield once adequate materials characterization tests such as fracture toughness have been demonstrated. Compos-

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Bouyancy Materials

A low density buoyancy material to provide adequate vehicle flotation characteristics is a key design tradeoff item on all deep diving submersibles (3). Present technology has qualified a syntactic foam—a composite of hollow glass microspheres in an epoxy resin matrix—of 42 lbs. per cu. ft. for 20,000 ft. operational depths. We are presently hard at work on a developmental program to reduce this density to the 30 lb. per cu. ft. range and still achieve a hydrostatic compressive strength greater than 13,500 psi and with negligible water absorption. The basic submersible weight saving using this new material represents a significant payload increase. Some of this technology has evolved from heat shield material development for reentry vehicles. More R&D is mandatory.

External Electrical System

Electrical cables, connectors, and penetrators for deep submergence applications have been a continuing problem since TRIESTE I. Electrical power partial or total failures obviously have an adverse impact on accomplishment of planned missions as well as a safety concern. Lockheed has had to qualify vendors in this area for the Deep Submergence Rescue Vehicle (DSRV) program (5,000 depth capability), and is currently running tests on cable assemblies under cyclic loads to 13,500 psi for Deep Submergence Search Vehicle (DSSV) qualification. This vehicle has an operating depth of 20,000 feet and a crush depth of 30,000 feet. Further work on aerospace multiplexing techniques to reduce the number of pressure hull penetrations is being explored.
Variable Ballast System

A variable ballast system is required to control buoyancy for varying descent and ascent rates on all deep diving submersible vehicles. There are two basic system approaches:

- to use expendable material such as lead shot which requires replenishment and therefore poses a logistics problem, and
- the use of sea water

One variable ballast concept using sea water, which looks promising, is a system with a sea water ballast tank, sea water intensifier pump, power source and system, and system controls. The system must operate against environmental pressure, 9,000 psi at 20,000 feet, plus at least 100 psi differential pressure to discharge the sea water, and no existing pumps have this capability. This high differential pump pressure requirement was resolved using pressure intensification by multiplying output pressure as a function of pump piston areas.

The hydraulic system, being pressure-compensated, operates at environmental pressure (9,000 psi) plus pump pressure of 3,000 psi totaling 12,000 psi. The viscosity of regular hydraulic fluid increases to an unacceptable level with increased pressure. Therefore, a low viscosity fluid must be developed which exhibits adequate lubricity and operational characteristics throughout the variable pressure range from the ocean surface to 20,000 feet. Piston pumps currently used in high performance aircraft must be redesigned to satisfy hydrospace operating requirements.

Power Systems

Advantages of nuclear power systems for long duration missions of both submarines and underwater habitats are undisputed. However, for small, deep diving submersibles having a 30 hour mission requirement, such a power system is not practical because of weight. Lead-acid and silver-zinc batteries are also prohibitive in weight for such a mission considering nominal energy storage requirements and sustained peak power levels dictated by the mission. Only fuel cells appear as a practical solution. Such a power system has secondary advantages as well, i.e., high efficiency, low volume and near-neutral buoyancy (4). As seen in Figure 4, two choices are under consideration for full prototype development. These are the H2-O2 encapsulated system derived from the space program and a free flooding pressure-balanced hydrazine system. Since the former is fully encapsulated in hard tanks, it suffers a weight disadvantage as a function of depth increase as compared to the pressure balanced system. The latter shows significant promise for deep submergence applications as the:

- free flooded pressure balanced systems operate at a few psi above environmental sea pressure regardless of operating depth, which eliminates the weight of system encapsulation and provides vehicle integration flexibility and design simplicity.
- reactants provide logistics, refueling and submerged endurance advantages.
- reactants specific gravity is nearer that of sea water thereby resulting in minimal buoyancy change with reactant consumption, hence minimum influence on vehicle trim.
- tests to date indicate an increase in operating efficiency as pressure/depth are increased.

A new concept utilizing aerospace technology which shows considerable promise for underwater use is a Thermal Chemical Dynamic Power System (TCDPS). It features a unique combination of established technology in the field of closed Brayton cycle power conversion, fluid storage and management, advanced combustion techniques, heat transfer, pressure vessel design, and development and system/vehicle interface expertise. For this concept to be successful, it will require application of established aerospace turbine power system technology to deep submergence requirements.

Information Systems

Currently satellites provide:

- required data for comprehensive world-wide weather forecasting by recording on a continuous basis global weather patterns.
- rapid precise navigational positioning information.
- world-wide communication networks.

However, these data systems cannot penetrate significantly beneath the ocean surface. Undersea operations require a completely different communication mode using acoustics and cables for information transfer purposes. Underwater sound transmission is restricted severely due to sound attenuation and refraction characteristics in the sea. Much developmental work in this and underwater navigation systems is required.

Life Support Systems

Of prime importance to either a spacecraft or deep submersible crew is a habitable environment provided for by a reliable, compact life support system. Either configuration has common elements:

- Carbon dioxide removal
- Trace contaminant control
- Oxygen supply
- Water/waste food management
- Temperature/humidity control
- Emergency systems

The most optimum system must be responsive to such factors as type of mission, crew size, weight/volume/power constraints and safety considerations.
Upon reviewing mission parameters, a parallel is readily apparent between space and undersea life support requirements. Initial work in submarine systems, particularly in the realm of non-regenerable life support, served as the basis for the original conception and requirement definition for the Mercury, Gemini, and Apollo spacecraft. The extremely severe constraints of weight, volume, and power on spacecraft resulted in an increase in the state-of-the-art knowledge of non-regenerable systems. This knowledge is now being used to provide sophisticated life support systems for small deep diving research submarines. These vehicles have comparable volume and power limitations as to that of current spacecraft.

The advent of the nuclear submarine with its vastly increased endurance and power availability gave rise to the development of regenerable life support systems which have proven to be quite successful. This technology will be used for the development of underwater laboratories and habitats.

Man-In-Sea Program

The present operational capability for undersea work by free divers is roughly 200 ft. with regular scuba gear and about 375 ft. with tethered "hard hat" equipment. The useful working period must be brief on each dive because of decompression requirements following each. This limitation has led to "saturation diving". Such diving exposes the diver to greater pressure of gases as a function of depth which essentially saturate the body fluids and tissues, and allows the diver to remain submerged for long periods of time. However, decompression periods when returning to atmospheric pressure are mandatory to safely remove these gases, otherwise bubble formations would occur causing "bends", disabling injuries, or even death. A rough rule of thumb is that an additional day of decompression is required for each added 100 ft. in depth.

The major area of technological development in this program is developing diving/decompression routines necessary with in situ operations at increased depths (possibly to 2000 ft.) and the associated equipment. Specifically,

- Improved diver communication systems which are less dense, helium-rich atmosphere.
- Improved diver suits with adequate thermal control, using techniques developed for Apollo crew suits, such as a heated water circulatory system but modified to provide desired temperature range. Complementary REU should continue.
- Development of diver work equipment to do useful work, e.g., power packs, special tools for the task at hand, mobility and stability aids, lights and visibility enhancement devices. More work is necessary in "reactionless" tools, taking advantage of the lessons learned on Gemini, etc.
- Small underwater support craft, ambient pressure habitats, tethered diver lockout chambers, and diver lockout submersibles.

Continued technology development in this area will allow man to work more effectively in a rather hostile environment.

Controls/Displays

Time and space do not permit reviewing all the design aspects of deep submergence vehicles. However, let's dwell for a moment on the interface between man and vehicle as to the type of controls and displays required. The variety of deep submergence missions plus commercial applications (e.g., offshore petroleum systems wellhead servicing on the ocean floor) have increased the operational degrees of freedom required as compared to the conventional sub. The latter involves primarily depth and heading control, but the former must also have precise control of surge and sway position and, of course, pitch and roll attitude. For those of you not familiar with submarine jargon, Figure 5 will be helpful. As you see, we still roll, pitch, and yaw, but now translation fore and aft is called surge, translation to port and starboard (left or right) is called sway, and for vertical movement, an expression that has been in wide usage for land lubbers gathered at the rail of a storm-tossed ship -- heave! With this new terminology fixed firmly in mind, it can readily be seen that for deep submergence rendezvous and mating operations, that all six degrees of freedom are involved just as they are in a Gemini docking exercise. Additional complications in the underwater world are variable ocean currents which must be contended with and poor visibility due to backscatter from particulate matter suspended in the water. Light optical imaging and acoustic imaging systems are being developed to cope with the latter problem.

The pilot controls the deep submergence vehicle's attitude in pitch, roll and yaw with the R/H controller, and translation in surge, sway, and heave with the L/H controller, Figure 6. Roll control is accomplished by moving mercury trim ballast; therefore, it is not a true control of roll because of the lag in response and the low degree of lateral stability with this type of vehicle. Precise pitch and yaw control is accomplished by operating vertical and horizontal thrusters located in the bow and stern of the vehicle.

Marine Engineering Handbook

Compiling a comprehensive hydrospace handbook should be given top priority so that the marine engineer will have at his fingertips data on environmental factors and their effect on materials and components relevant to ocean systems design tasks. It is recommended that this have a format similar to the USAF, "Handbook of Geophysics" and "Aerospace Materials Handbook". The latter provides design data for aircraft, missiles and spacecraft applications.
Focusing on a deep submergence vehicle on routine search operations is very much like flying an aircraft on the "gauges" because of limited visibility (approximately 30 feet). A trained instrument pilot will adapt quickly to this new machine because of his inherent knowledge of controls, displays, systems, operating techniques and response to emergencies when the pucker factor goes up.

One of the deep submergence vehicle problems is having adequate sensor information properly displayed. Viewports, video displays, acoustic and optical imaging systems provide Mark I eyeball assets to augment the sonar systems developed originally for current military subs. Sonar systems continue to improve but we need to make major strides toward gaining knowledge of acoustic energy propagation in the ocean at all operating depths. Currently, we depend on forward and side looking sonars as the eyes and ears of our submarine and ASW crews. Unfortunately, this gear has limited capabilities. Therefore, we must learn more about the eccentricities of the sea before hardware can be perfected to give the detection capabilities desired.

Maneuverability and hovering controllability requirements, being key design items, dictated the need for an integrated control system. These capabilities really pay off during precise mating/docking operations and for dexterous use of manipulators on arduous tasks. Continuing work is essential on manipulator design to improve capabilities and ease of operation (particularly at deeper depths) just as in space operations. Mission simulators are an excellent means of developing our capability in this regard as an engineering tool for vehicle stability and control evaluation prior to hardware commitment.

A major and overriding design consideration in any manned deep submersible is that of crew safety. Critical failure modes of all components which would endanger the life of the crew are determined, their probability of occurrence defined, and adequate safeguards provided to preclude the creation of hazardous situations. Submarine safety specifications, certification requirements, the boat's reliability program, and the supporting component development test programs, all come under critical scrutiny and action as necessary by the program office and operating crews just as in aircraft/ spacecraft programs.

DEEP SUBMERGENCE RESCUE VEHICLE (DSRV)

Let's take a quick look ahead at the Navy's Deep Submergence Program. The DSRV-I (Figure 7) was officially christened on January 24th. It will be involved in sea trials off San Clemente Island later this year. This boat has an operational depth capability of 5,000 feet. Its prime mission is to rescue 24 men at a time from a downed submarine. We sincerely hope there is never reason to fulfill this mission but instead that it will be gainfully employed accomplishing alternate missions, e.g., oceanographic research, search and recovery, developing deep ocean operational "know-how", etc.

Since the DSRV must have the capability to accomplish crew rescues down to the collapse depth of our current combatant fleet, it is mandatory that mating between the vehicles be performed expeditiously and safely. This mating requirement -- "joining some device to the escape hatch of a disabled submarine to transfer its personnel to safety" (5) -- was the principal factor governing the design of the DSRV subsystems. Design performance requirements specify that the DSRV must be capable of effecting a mate to the deck of a disabled submarine at any angle up to 45 degrees from the horizontal in the presence of a one-knot current. This task must also be done expeditiously, particularly if the downed sub's crew is in jeopardy. Being able to mate on a routine basis was considered to be the most important factor governing design of the DSRV and represents one of the toughest operational challenges ever tossed to a pilot.

The design and development of this vehicle represents a major technological advancement for probing deeper into the deep ocean secrets. It is paving the way for its new brother, the DSV, in economic and military pioneering of the depths.

DEEP SUBMERGENCE SEARCH VEHICLE (DSSV)

The next DSSF project, the DSSV (Figure 8), is now in the design phase. It has a provocative goal to live up to -- that of descending to depths of 20,000 feet on specific search and object recovery tasks.

COMMERCIAL OCEAN-GOING VENTURES

Let's shift gears and look at two commercial enterprises of paramount interest. The non-living resources of the sea -- oil, gas and minerals -- contribute significantly to this nation's economic growth. Conservative estimates are that world petroleum consumption will triple in twenty years. This rate can be attained only by extensive offshore petroleum activities.

Offshore Petroleum Systems

Offshore petroleum exploration and development operations have encountered a sharp increase in conventional drilling and production costs. Particularly at depths of 400 feet or more, fixed surface structures represent large investments, are plagued by weather, present hazards to marine traffic and, at times, result in civic-political problems. Currently, petroleum companies are capable of putting into production, oil wells at continental shelf depths (600 feet).

Technology to circumvent these problems is developing rapidly under the impetus of industry rather than government funding. Lockheed has a system
underway which will double this depth capability (1200 feet) and eliminate many of the ocean surface interfaces (6). (See Figure 9.)

In this new system, individual wellheads are encapsulated on the ocean floor within pressure chambers called wellhead cellars. The products of the wellheads flow into a manifold center installed on the sea floor which is also maintained at atmospheric pressure. Here the fluids from each well are controlled, co-mingled, and then transported by gathering lines to a separation facility. The manifold center, Figure 10, also has necessary controls to divert individual wells for testing. An anchored floating platform or fixed structure may serve for support of the separation facility. Locations that possess deep water reservoirs near shore may allow for on-shore production equipment installation.

Manned attention at the subsea wellhead or manifold center is provided by submersible atmospheric capsules that operate from support ships. The capsules contain their own propulsion system for maneuvering into place over the wellhead cellar or manifold center. They attach themselves to the subsea structures by engagement of a gasket-type seal. An operational sequence is shown in Figure 11. An electrical power for the propulsion system, for the onboard equipment and an air supply are provided by umbilical cables from the surface support ship. The capsule work chamber is maintained at a one atmosphere shirtsleeve environment. It contains the conventional oilfield equipment that trained oilfield personnel are familiar with and use in operations that duplicate those performed on land or on platforms. In effect this total system concept is based upon the adaptation of standard oilfield methods and equipment for subsea use. Future designs of ocean floor automated production control systems can benefit from aerospace multiplexing techniques coupled with computer technology expertise.

Ocean Mining System

The world-wide shortage of nickel has caused suppliers to seek ways and means of recovering nickel from the sea. An excellent source is manganese nodules. These are composed principally of manganese, nickel, and copper. The real "hooker" is that those with the greatest mineral content are found in the deep Pacific Ocean basins (12-18,000 ft.). Cost effective recovery systems to harvest these nodules, including bringing them to the surface (rock in the box!) and beneficiation methods, pose major technological challenges.

TEST BED VEHICLE

How can we best improve our technology base now to make certain that we will have proven hardware for strategic and tactical submarines, manned under-water habitats, offshore petroleum and ocean mining systems of the future? Certainly as a first step, we should take advantage of the lessons learned from aircraft and spacecraft development. One of the predominant means was the use of a test vehicle to prove out performance, reliability and safety of prospective subsystems and their components (?).

As a case in point, the C-5A military transport was designed with four General Electric TF39 engines rated at 41,100 lbs. thrust each. This engine has many unique features such as an 8:1 bypass ratio, and a 5,55:1 thrust to weight ratio. To give you a feel for the size of the C-5a Galaxy - it is the world's largest aircraft with an overall length of 246', wing span of 223' and a tail length of over 65'. The maximum gross weight at 2,25 "g" is 764,500 lbs. You can readily see the impact of putting untried engines into this behemoth. We therefore worked with the engine manufacturer, General Electric, to have them qualify their engines in flight using a test bed. Only a B-52 could handle this mission as the outside capsule diameter is over eight feet and length twenty-six feet. This was accomplished by removing the two engines in the number 3 pod of a B-52 and replacing them with one TF39 (8).

The B-52 test bed verified or showed shortcomings which were subsequently corrected in basic engine performance and thrust levels, specific fuel consumption, fan speed envelope, engine component performance, windmilling air starts to 45,000 feet, core and fan vibration, in-flight thrust reversing, and in-flight anti-icing flying behind a KC-135 tanker equipped with a waterspray rig (a novel way to have an icy shower). Such a flying test bed allowed evaluation of engine operation, particularly transient characteristics during various load factors and extreme angles of attack and sideslip. This type of testing could not be done in a ground facility.

By this early TF39 flight testing many unforeseen problems were resolved. Thus, redesign was initiated at an earlier date and in addition, having witnessed actual performance on the B-52, we had no misgivings on our first flight aboard the C-5A.

For deep submersibles, the Navy sorely needs propulsion systems that can operate reliably and safely at deeper mission depths, have longer life, are lighter, more compact and have lower noise levels. Here then is an excellent opportunity for a deep submersion test bed vehicle to be put to work.

The Navy has taken a major step forward with the implementation of the Deep Ocean Technology (DOT) program released as an Advanced Development Objective by CNO on 4 January 1968, with its express purpose "to provide an advanced, general purpose, technology base from which technological options for future deep ocean weapon systems may be selected. It will provide the advanced undersea capability now being developed in related current programs or projects. This capability is vital to optimize the effectiveness of current warfare systems and is essential to the development of new, future systems. The project is oriented primarily to current and potential deficiencies in the existing technologies, and will permit the Navy to
operate effectively in the total ocean, if and when future Navy missions require such capability. One of DOT's objectives is the development of a Manned Submersible Testbed (MST) that will be operated to 20,000 feet. Its purpose will be to evaluate and test:

- Advanced structures and materials.
- Energy/power/propulsion systems and components.
- Auxiliary machinery such as variable ballast systems.
- Life support and safety requirements.
- Unmanned work systems operable from the MST.
- Information systems to provide precise navigation, guidance, control communication and amplification of the pilot's eyes through optical and acoustic imaging systems.

The need for a deep submergence test bed to have already developed, tested, and made ready pertinent operational systems was graphically portrayed during the search and recovery of the nuclear bomb off Palomares, Spain. One of the conclusions reached was none of the ships, vehicles, boats, DSVs or other equipment were specifically designed for the task at hand. All showed deficiencies of one kind or another.

By having such a test bed submersible to prove out vehicle subsystem and components, it becomes readily apparent that a naval architect can proceed with confidence, that his system can meet its design objectives, that his weight analyses will be accurate and that he can better meet tight schedules as defined by the program manager. The latter can proceed with a credible program plan which with efficient management can reasonably make all its milestones within budget. The customer will in turn know that he has a "cost-effective" system which should operate reliably, meeting the operational requirements stipulated.

**CONCLUSION**

In summation, I have tried to give you a better understanding of the ocean environment, the application of technology in problem solving, and a feel for some of the operations involved in penetrating inner space. The ocean is a tough environment! It does not give up its resources readily. Therefore, by taking advantage of new techniques and technology evolving from aerospace systems and applying relevant knowledge judiciously to underwater applications, man can master this challenging area much more thoroughly and productively. Environmental phenomena can then be measured and predicted more accurately. In some cases, control can be achieved which is mandatory where pollutants are involved. New sensor instrumentation, data retrieval and processing systems are a must in the immediate future. The latter can be aerospace derivatives, but the former need further development. To put it bluntly, our country is in dire need of an aggressive technology program to effectively penetrate the sea. The time is here to "Press On"!

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Figure 1. Submarine Systems Weight Fractions.
Figure 2. DEEP QUEST - Three Views.
Figure 3. Bisphere Model.
Figure 4. Fuel Cell Power Curves.
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Figure 6  Hand Controller Modes
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