Underwater Systems Within the Scientific, Technological, and Economic Framework

Carl F. Kottler Jr.
Grumman Aircraft Engineering Corporation, Bethpage, N. Y.

Introduction

THIS paper presents the economic and technological framework within which advanced underwater systems will fit. Any manufacturer-developed underwater system must meet reliably the needs of a customer who has the financial capability to capitalize on its use in performing a particular mission or carrying out some operation. The ocean-based system must compete economically with existing and possibly land-based, airborne, or satellite systems. In addition, the hardware and vehicular subsystems must conform to existing or readily acquired design and fabrication capabilities of the company designing the system, based on a reasonable extension of past performance and experience.

Water-based systems are unusually attractive in exploiting the ocean's resources whenever land-locked sources are in the process of being rapidly depleted or possibly are not sufficient to meet an increasing demand. Also, advanced underwater systems may fill an operational void, particularly when the needs of the nation and the military are extrapolated, considering the significant advances being made and systems that are becoming feasible through marine technological innovations.

To establish the required framework for advanced underwater systems, it is necessary 1) to examine the probable financial commitments and system requirements of potential governmental and industrial customers engaged in exploiting the sea for political, military, commercial, or recreational purposes; 2) to assess briefly the capabilities and past experience of the aerospace industry as applied to underwater systems development; 3) to examine the state-of-the-art of marine technology; and 4) to consider a representative group of missions and operations. From this framework, we hope to determine which advanced systems, component vehicles, and associated hardware should receive a more detailed feasibility study. These considerations are examined in further detail in the following sections of this paper.

Potential Customers

The techniques needed for designing and fabricating outer and inner space vehicles are very similar in many respects, but the organizational/economic framework for the exploitation of the oceans is somewhat different from that needed for the exploration of outer space. The huge capital investment in proportion to the relatively meager financial gains expected from outer space activities requires almost complete funding by the U.S. Government with industry supplying contracted hardware and services. The benefits are strictly of an intangible nature such as national prestige, advancement of scientific knowledge, and military potential.

These benefits certainly will also accrue from oceanographic work. However, where technology has advanced to the point of demonstrating feasible, commercially adaptable systems, economic incentives should draw industry to participation in their further exploitation.

Industry has made large capital investments in developing and harvesting the more accessible resources of the sea and has demonstrated its tacit acceptance of responsibility in this area. Industry's efforts in this direction have been greatly assisted by the U.S. Navy's extensive operational experience, basic research, and support of education associated with its prime responsibility, i.e., national security. Also, numerous nondefense governmental agencies have contributed significantly to the present level of oceanographic knowledge. Thus, the Presidential Panel on Oceanography[1] has recommended a continuance of this three-way split of responsibility regarding undersea activities: 1) U.S. Navy—national security, 2) industry—commercial exploitation, and 3) governmental agencies (nondefense)—additional services.

The annual expenditures by the governmental agencies engaged in oceanography, along with the capital investment and annual sales of representative industries committed to exploiting the oceans, provide the economic framework within which the national oceanographic effort is operating. Federal expenditures for marine sciences and technology are presented in Table 1. Industry's participation is shown in Table 2.

Table 1 indicates that a large proportion of the available government funds for oceanographic purposes is being used by the Department of Defense (primarily the Navy), a substantial share of which is allocated for the Deep Submergence Systems project. The sizable commitment to exploiting the sea by industry, in particular the petroleum industry, is readily apparent from Table 2.

At present, there does not seem to be any impending spectacular achievement by the Soviet government within the marine sciences which might require an order-of-magnitude increase in the U.S. funding of oceanography. Therefore, the Presidential Advisory Panel on Oceanography has recommended a rather modest $150 million increase in governmental spending mainly in research and the Navy's security-related oceanographic efforts. The panel has *not* seen the need for extensive reorganization within the government to create an inner space agency comparable to NASA, but rather envisions combining some non-Navy oceanographic activities under one agency. This agency would be responsible for the

Carl F. Kottler Jr. has been doing research and development work in the aerospace industry during the past 18 years. He received his B.S. degree in physics from Adelphi University in 1962. Since then he has done graduate work in mathematics and more recently in oceanographic engineering in the Marine Sciences Division of C. W. Post College. He was a member of the Apollo Mission Planning Task Force (AMPTF). He is currently working on advanced oceanographic configurations and solar radiation studies within the Special Projects Section of the Research Department at Grumman Aircraft Engineering Corporation. He is a Member of the AIAA.

Received January 29, 1968; revision received October 16, 1968.

description, prediction, environmental modification, and development of the ocean's resources. The new agency would bring under one organizational roof: the Environmental Science Services Administration (ESSA), Geological Survey, Bureau of Commercial Fisheries and (Undersea) Mines, and some of the Coast Guard's oceanographic activities.

Whether any or all of the panel's recommendations will in fact be carried out, and in what final form, only future developments will tell. In any event, it seems probable that the Navy's support through the Office of Naval Research (ONR) and its laboratories will continue. During 1968, the National Science Foundation began implementation of university support through the National Sea Grant Program which is oriented to develop information and processes to assist industries in the development of the resources in the oceans, particularly in the shelf areas. Funding was $5 million during the 1968 fiscal year. This is scheduled to increase to $6 million for 1969 and $15 million for 1970.

An alternative approach that has received some consideration is to expand NASA to encompass oceanographic activities, thus unifying and broadening the base of technology by means of a balanced search for scientific knowledge on all frontiers, including those of inner and outer space. The advantages of such an approach are as follows.

1) A minimum of organizational disruption. Most departments within NASA would merely expand their areas of responsibility in a natural way either by broadening their capabilities, redirecting activities, and/or by adding oceanographic specialists where needed.

2) If the necessary funding for oceanographic activities increases at the same time as that for outer space activities decreases, then the over-all shift in funding would be within the same organization and would be noticeable only as a shift of emphasis to other national goals.

3) The existing contractual relationships would remain intact between the government and those aerospace companies that are developing the required capabilities for the design and fabrication of hydrospace vehicles.

This, then, is the present and possibly the future framework within which any advanced underwater systems must develop. There is obviously a great need for new methods as well as the combining of existing techniques to solve a number of important problems facing the nation and the world, particularly the following.

1) The increasing demands of an expanding population for food can be met by improved systems applied to harvesting the vast fish-protein resource of the sea.

2) The world's mineral needs are in part being met through the present exploitation of petroleum and gas beneath the continental shelves, and the ocean may in the future yield increasing amounts of other minerals and chemicals as well. However, new techniques are needed to solve the adverse weather threat to offshore installations and to extend petroleum exploitation to the land beneath the open oceans.

Table 1 Federal oceanographic program budget

Department or agency	1967, $\$ \times 10^6$	1968, $\$ \times 10^6$	1969, $\$ \times 10^6$
Defense	278	257	298
Interior	64	74	76
National Science Foundation	25	38	41
Commerce	35	38	38
Transportation	8	11	33
Atomic Energy Commission	11	13	12
Health, Education, and Welfare	8	6	8
State Department	5	5	5
Agency for International Development	2	3	3
Smithsonian Institution	2	2	2
NASA	...	2	2
Total	438	449	518

Table 2 U.S. industry oceanic exploitation

Industry	Capital investment, $\$ \times 10^6$	Annual sales, $\$ \times 10^6$
Petroleum (oil and gas)	12,750	910
Mining		
Sand, gravel, and shells		50
Sulfur	35	37
Platinum dredging		2
Chemical (minerals from sea water)	300	117–127
Desalinated sea water		8
Fishing	1,400	500
Maritime		
Marine engineering (shipbuilding, salvage, and harbor work)		2,500
Transportation (freight, passenger, and port income)		11,500
Secondary outlays (trade employment and income)		8,000
Recreation (boating, diving, etc.)		4,000

3) By proper pollution control, the recreational potentialities of the seas, seashores, rivers, and lakes may be used to help satisfy the needs of our expanding population's increase in free time. All of these problems demand our return to the sea with renewed interest and require the development of the systems, advanced underwater configurations, and the tools ultimately necessary for their solution.

Inner/Outer Space Technology

Much of the experience that industry has gained in extending technology into outer space can now be applied to solving the problems of inner space. The solutions to these problems are being facilitated greatly by using the systems and operations analysis techniques which have been highly developed in their application to outer space systems. For example, the operational techniques of rendezvous and docking are certainly applicable to underwater search, salvage, and rescue operations.

Both outer and inner space vehicles require a carefully regulated cabin environment supplying oxygen at just the right pressure, temperature, and proportions to other gases so as to maintain a reasonable degree of crew comfort and safety. The outer space system may utilize a pure oxygen breathing atmosphere at relatively low temperatures (75°F) and less than atmospheric pressure (3.7–5 psi) for ease of transition to extravehicular activities (EVA). The hydrospace vehicle, on the other hand, may be designed for an 80% helium/15% nitrogen/5% oxygen system to reduce oxygen toxicity effects. A temperature of 90°F will probably be maintained to offset heat losses due to using helium; and high pressures on the order of 100–200 psi will be needed (as in the case of the Sea Lab and the Conshelf operations) to permit saturation diving.

The psychophysiological problems of extravehicular excursions during inner/outer space missions are quite closely related. The astro/aquanauts need space suits with either portable breathing gas supplies or tethers of the "hookah" type. The suits themselves must provide adequate protection against heat or cold during what may be somewhat stressful conditions induced by weightlessness, disorientation, or anxiety.

Auxiliary equipment and special-purpose tools must be designed for use in the new extravehicular environments, including locomotion-assisting devices for longer excursions. Examples of the latter range from the simple devices of hand holds or flippers, to hand-held or body-mounted jet propulsion devices, and to undersea sleds or lunar roving vehicles. The viscous effects or lack of them sometimes aid and sometimes hinder operations. In general, experiments in the one environment may readily be a proving ground for gaining ex-

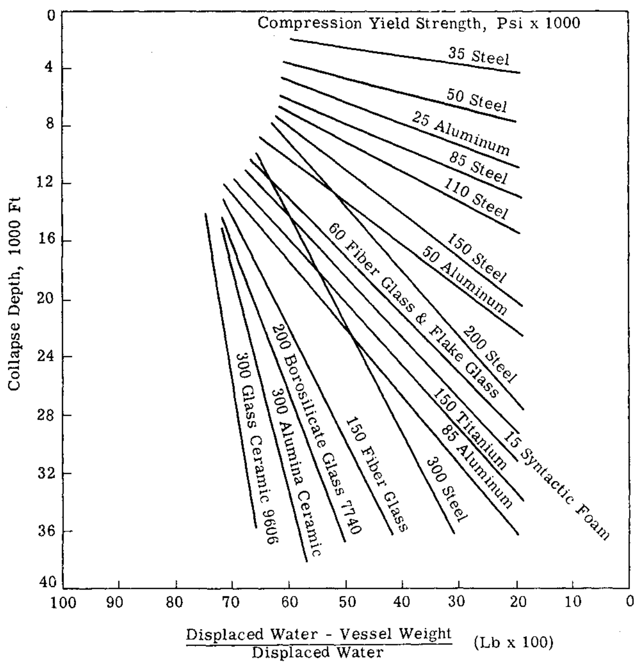

Fig. 1 Comparative material strength of rib-stiffened cylinders (from Ref. 6).

perience applicable to the other environment. Commander M. Scott Carpenter's dual participation in the Man-in-the-Sea project as well as the space flight programs and the underwater extravehicular activity simulation and training of Astronaut Edwin E. Aldrin Jr., prior to his Gemini 12 excursion, are typical examples of the interrelationship existing between inner and outer space activites.[2,3]

Large payload-to-displaced-weight ratios of deep-submergence vehicles will be needed and attainable only through stringent weight control and the application of new materials. Weight-saving techniques by means of new fabrication methods as well as the development and application by the aerospace industry of what were at one time considered exotic materials have solved the atmospheric re-entry problem. Similarly, the application of massive glass, glass-ceramics, filament-wound fiberglass, or new materials in combination with conventional materials will permit efficient operations within the ocean's depths.

Also, the requirements of reliability of equipment and systems as a whole are particularly stringent in both inner and outer spacecraft where the safety of astro/aquanauts is of primary concern. The Man-in-the-Sea program revealed the need for reliable equipment properly tested under conditions simulating the high pressure and highly corrosive environment of inner space.

Marine Research

Oceanographic Research

Oceanographic research is not merely recording the velocity, temperature, and salinity fields of the sea for their own sake, but is seeking to discover those regularities necessary to establish general laws that may explain oceanic events and form a basis for prediction. The increasing use of the sea for scientific purposes, underwater habitation, military missions, and commercial exploitation requires a precise description, as a function of time, of the ever-changing oceanic environment.

Commercially, sudden storms with accompanying wave damage to shore and continental-shelf emplacements cost many lives and large sums of money, both of which could be considerably reduced by advance warning. Militarily, the accurate prediction of oceanographic conditions is needed by those engaged in naval surface and subsurface operations. For example, the accurate prediction of environmental conditions would double the effectiveness of antisubmarine warfare.[4] However, only from the analysis of sufficient pertinent data will come the techniques with which to predict environmental changes reliably. Such foreknowledge is necessary for the safety and efficiency of both undersea and surface operations.

Deep Submersibles and Materials Research

Special-purpose manned submersibles are evolving for operations at various depths. Since the operating depth of a submarine is limited in many cases by the strength of its hull, and since the largest single weight item is the hull, any effort to extend significantly the submarine's capabilities must be done through weight savings achieved on the hull. Therefore, there has been particular emphasis upon utilizing new improved hull materials so as to 1) increase the payload carrying capacity, 2) increase the depth capabilities, 3) increase velocity and submerged duration, 4) increase safety and reliability, and 5) at the same time decrease cost and maintenance.

The single spherical steel pressure vessel of the Trieste has evolved successively into 1) a faired, single sphere of HY-100 steel* used for the "Alvin" and the HY-80 steel "Deepstar"; 2) a bispherical (200,000 psi yield strength, maraging steel) pressure hull for the "Deepquest"; and 3) the trisphere (HY-140 steel) to be used in the "Deep Submergence Rescue Vehicle." One concept, the "Willm Bathyscaph",[5] combines as many as five spheres to form the pressure hull. In addition, cylindrical pressure shells of steel and aluminum have been developed as exemplified by the Dolphin (HY-80 steel) and the Aluminaut (7079-T6 aluminum). A large percentage of the deep submersibles (e.g., Aluminaut, Archimedes, etc.) rely on the fail-safe technique of using electromagnetically held steel pellets for ballast and for changing buoyancy, which was developed for the Trieste.

Military submarines are severely limited because of the sacrifice of pressure hull depth capability in favor of using conventional hull materials and carrying large payloads at high speeds for long submerged durations. One of the major parameters which gives a measure of the structural efficiency of a submarine's hull is its compressive yield strength. Figure 1 (from Ref. 6) presents a comparison between various metallic and nonmetallic rib-stiffened cylinders. The higher the ratio of the displaced water weight minus the vessel weight to the displaced water weight, the higher the payload-carrying capacity (assuming that all the other parameters are the same). This figure shows that only glass and/or ceramic hulls can withstand the pressures of great depths without compromising the payload-carrying capacity of the submarine. Thus, the only foreseeable method for increasing operational depths by an order of magnitude is to use the increased strength-to-weight ratio materials of the glass-ceramic group. Similarly, commercially feasible submersibles can only operate at increased depths by going to these more efficient materials, which will permit the large payload-to-displaced-weight ratios necessary for competing economically with other systems.

Preliminary studies of various pressure hull materials have been made by various private industrial organizations, as well as by the U.S. Navy. Tradeoffs between the advantages and disadvantages of the different materials have resulted in many successful submersibles covering a wide range of missions. However, a large increase in the load carrying capacity of materials applied to submarine technology is needed to achieve a truly efficient deep submersible.

There are indications that the search for these materials, and research, should be intensified in the direction of glass and/or ceramics for marine applications. Indeed, there has

* HY-100 steel has a compressive yield strength of 100,000 psi.

already been considerable preliminary work done in the study, fabrication, testing, and actual design and construction of manned and unmanned submersibles using glass as a pressure shell material. Particularly valuable work has been done by H. A. Perry of the U.S. Naval Ordnance Laboratory. In one of his studies,[7] he verified experimentally the explosion resistance of glass pressure hulls. Glass cylindrical and spherical models actually *increased* their resistance to bending loads and to dynamic explosive pressures with increased depths (see Fig. 2).

In contrast, the thick metal shells required for achieving moderate depths have a number of disadvantages, besides their extremely low payload/displacement ratios, when compared to glass. The required high yield strengths of steel, aluminum, and titanium are susceptible to 1) brittle fracture, 2) corrosion (steel) and pitting (aluminum), 3) plating and cladding deterioration, and, most importantly, 4) *decrease* in strength with increasing depth due to their low compressive strength, as shown in Fig. 2.

The very high compressive strength of glass permits an increase in strength with increased operational depth. This fact combined with the many other advantages of glass, such as 1) its high corrosion resistance, 2) creep resistance, 3) high strength/weight ratio, 4) low cost, and 5) transparency, has led to the forecast of glass as the pressure vessel material for submersibles of the future.[1] Exploratory investigations have shown that probably all of the problems of applying glass to this new use are solvable. However, further experience in building composite structures of practical sizes is needed. The development and testing of new materials, as well as the design and fabrication techniques associated with what amounts to an entirely new application of glass technology, will require considerable effort in order to gain the confidence of submarine designers, manufacturers, and users.

Underwater Missions and Operations

The sea, with its vast resources and its use as a supply route and, in times of war, as a platform from which to mount military attacks, has been of great value to those nations sufficiently capable to understand and utilize it. The recovery of resources from the sea has been a particular challenge to man since the beginning of time. This challenge is now being met more fully by the scientific-technological community which is providing answers to significant questions and is developing systems for exploring and utilizing hitherto inaccessible reaches of the oceans. The resulting conquest of the sea will, in all probability, be a blend of governmental, military, and commercial missions with homesteading operations opening increasingly larger areas at greater depths for exploitation.

Homesteading

The continental shelf, with a slope averaging less than $\frac{1}{8}°$, is a subsurface plain adjacent to most large land masses. It extends from the mean low water line to the point where there is a marked increase in gradient. This point is the beginning of the continental slope which has an average gradient of 4° but frequently reaches 25° in its plunge to the floor of the deep ocean basins. The sharp break point in gradient which separates the continental shelf from the continental slope is generally at a water depth on the order of 200 m, averaging 42 miles from shore but in some places 750 miles seawards.

The International Convention on the Continental Shelf states that coastal nations have *sovereign rights* over their adjacent continental shelves "to a depth of 200 m or *beyond that limit* to where the superjacent waters admit of the exploitation of the natural resources of the said areas." Virtually all of the sea bottom is thereby explicitly opened to "homesteading" and the evolution of manned and unmanned subsurface emplacements permits the encompassing of vast oceanic bottom areas by those nations that are so inclined.

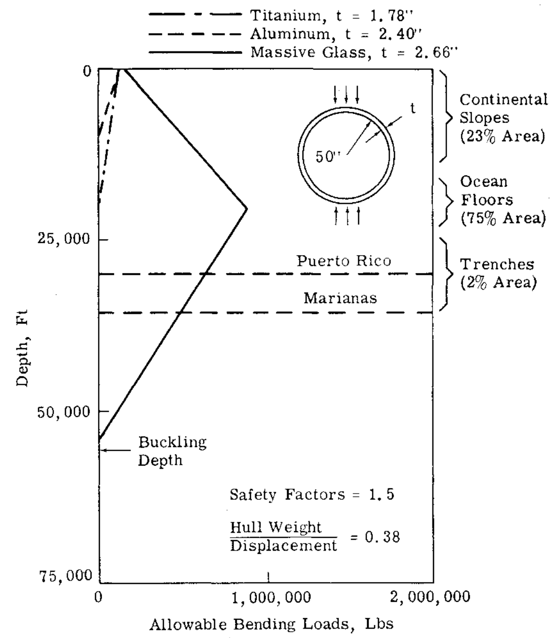

Fig. 2 Theoretical effect of depth on allowable loads of spherical shells (from Ref. 7).

A number of experiments, projects, developments, and feasible extensions of existing vehicles and systems could conceivably be combined to yield commercially competitive systems operating at underwater homestead sites. The exact time and manner in which these independently evolving fragments should be combined requires further study and is beyond the scope of this paper. However, a number of general trends may be examined and conceptually combined.

Significant factors pertaining to the exploitation of underwater petroleum reserves, are apparent in the following examples.

1) Dr. Jacques Piccard's excursion to the bottom of the deepest part of the sea has shown that man can readily be provided with a protective environment for bottom habitation. A time extension would allow operations at these depths.

2) The U.S. Navy, with its Man-in-the-Sea experiment, and others have conclusively demonstrated the feasibility of underwater habitation for time periods up to six weeks with productive extravehicular excursions of the saturation diving type on at least the continental shelves (see subsection on diving).

3) Oil- and gas-producing geological structures are in many instances related to salt domes.[8] On land, dissolving the salt in shallow salt domes has provided cavities for oil storage. The same technique could be applied to underwater sites.

4) Many offshore drilling operations are suspended during bad weather and heavy seas, sometimes catastrophically. The petroleum industry is particularly anxious to emplace all oil drilling operations on the sea floor to eliminate weather-induced downtime, reduce vulnerability to hurricanes, and to simplify operating procedures.

An idealized commercial homestead for exploiting the petroleum resources of the bottom of the sea is now readily visualized. It would consist of a series of bottom-emplaced oil wells with sufficient proven reserves to justify the capital investment in the site. The oil would be pumped into adjacent submerged tanks or into a cavity in a nearby salt dome. Submarine tankers with automatic hook-up attachments, possibly similar to in-flight refueling probes, would then take on oil from these storage areas for subsurface shipment to refineries and users.

Sulfur is believed to rank second only to oil and gas in potential as an exploitable mineral of the shelf areas in the Gulf of Mexico. It is usually found in the cap rock of some salt

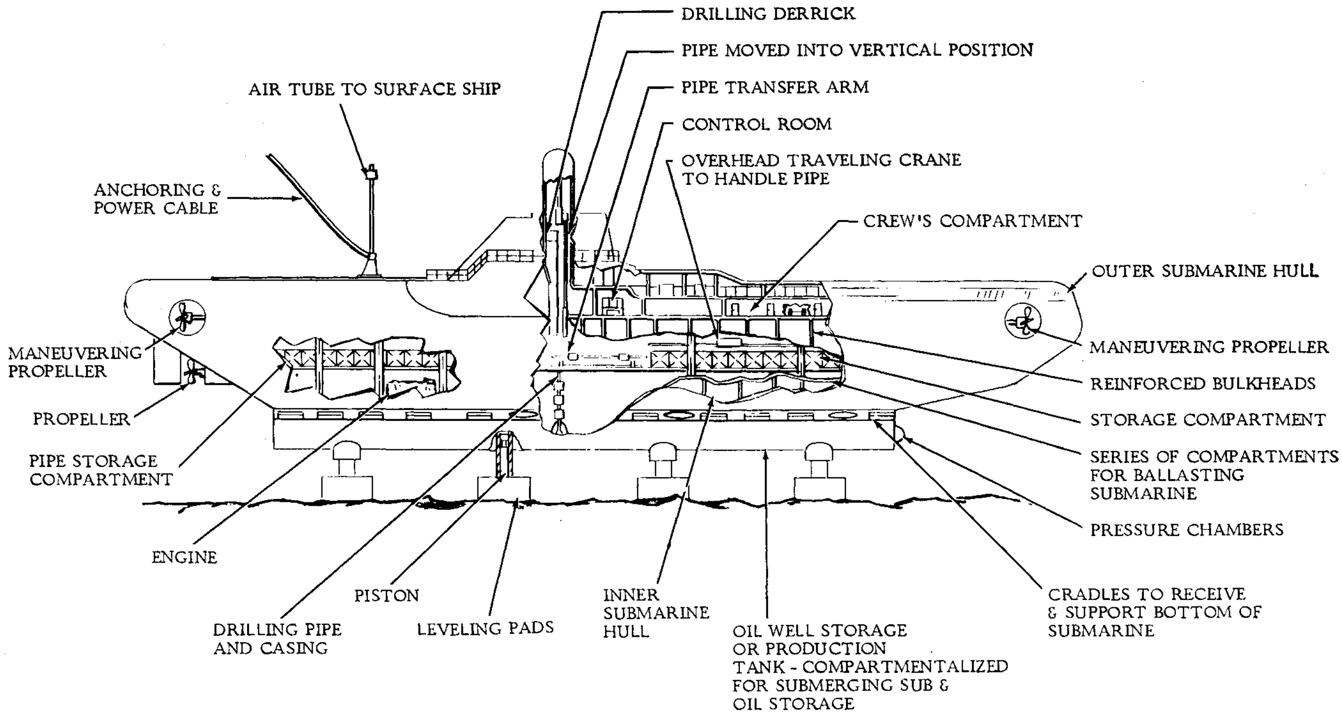

Fig. 3 Submarine automatic oil well drilling machine. (Submarine designed by J. V. O'Neill, G. Homanick, and R. C. McCord for drilling on the sea floor; reproduced by permission of Automatic Drilling Machine Inc., Dallas, Texas).

domes. Eighteen of the 230 salt domes discovered in the Gulf of Mexico up to 1956 contained sulfur in sufficient quantity and quality to make its recovery commercially competitive.[8] This occurred despite the fact that the effort required to exploit a deposit of ore is an order-of-magnitude more difficult than that required to recover oil.

Sulfur is in ever-increasing demand by industry. Very few reserves on land are being discovered, whereas those that are known and are of good quality are rapidly being depleted. The resulting escalation of prices makes the exploration for and recovery of sulfur from underwater sites more and more attractive. Efficiency and safety of operations could conceivably require homestead mining for sulfur from self-contained bottom emplacements similar to those envisioned for oil wells. Again, submarines designed especially for logistic operations would be required.

The offshore sulfur mining industry has been in a particularly fortunate position. First, the discovery of sulfur sites has been somewhat of a spin-off from oil exploration since the petroleum industry has also been seeking out salt domes for their attendant oil and gas reserves. Secondly, it has become competitive in price with land-locked sources. Thirdly, recovery techniques are adequate to get offshore operations started. Profits from this approach can thus be reinvested in the development of improved recovery techniques.

In contrast, the advantages of mining other minerals from sea-bottom sites are not readily apparent. Since known sources adequately satisfy present industrial needs, capital is not available to search out or to test the extent and quality of even shallow water sites. Consequently, there has been no need to improve on the old bucket dredge technique. Unless the government anticipates future needs, and supplies the necessary impetus for exploration, the development of the techniques necessary for competitive exploitation of undersea minerals other than oil, gas, and sulfur from homestead sites, is clearly not going to proceed very rapidly, if at all.

There exists a large number of sea mounts and ocean ridges, some of which rise 12,000 ft above the ocean floor and to within 6000 ft or 8000 ft of the surface. Scientific emplacements on these sites or possibly military outposts would be of great use. Undersea habitations could serve as ocean environment sampling stations, submerged acoustical communication and navigation centers, as well as geological camps or bases of operations for geological survey missions. Militarily they could serve as submarine supply and repair facilities, fixed launch platforms, and underwater acoustical observation outposts which would be safe from the radioactivity and the overpressures of nuclear attack.

One preliminary step towards homesteading the sea bottom should be increased research efforts aimed at developing corrosion- and pressure-resistant materials and structures. Advanced glass technology provides an avenue of approach which could be unusually rewarding. Glass and ceramics may be tailored to meet a wide range of requirements. Because of their low cost in quantity production, their depth hardening, and their corrosion resistance, they could be used for a variety of undersea applications including: 1) structural materials for hemispherical or cylindrical bottom emplacements with panoramic viewing; 2) pressure hulls for deep submergence logistics vehicles; 3) syntactic foam flotation devices; 4) deep sea corers; and 5) pipes, valves, and ball joints.

A number of firms have developed commercially successful underwater systems based on the Sea Lab and the Conshelf experiments.[9,10] The use of helium-oxygen breathing systems and saturation diving techniques have increased the efficiency of divers manyfold. However, the perfecting of gilled breathing systems, fuel cells, small nuclear power plants, and desalination systems is needed to make manned underwater emplacements more self-sufficient. This would help to ease the present logistics problems associated with sustaining men on the ocean bottom.

Commercial Exploitation

Offshore petroleum deposits are receiving by far the greatest exploitation effort at present compared to the other resources of the sea. Considerable research and development work is aimed at emplacing the wellhead on the ocean bottom in order to increase efficiency and to reduce the chances of catastrophic disruption of drilling operations by weather-generated surface phenomena. The Sealab projects in this country and the

French Conshelf series, although taking different approaches, both revealed their vulnerability to the vagaries of weather.

The Sealab I experiment went to great pains to select a site near Bermuda which had not had any hurricanes for a considerable length of time. In spite of this precaution, the stay time on the bottom had to be terminated because of an approaching hurricane, the first in 22 years. The recurrence time is, coincidentally, the same length of time as the average 22-year solar cycle when both magnetic orientations of sunspot pairs are considered.

Similarly, the Conshelf Three project encountered a severe storm with the heaviest swells in 19 years threatening to cut the power line between the sea bottom emplaced aquanauts and their shore-stationed generator. Through great efforts, disaster was averted. After the storm subsided, the aquanauts stayed at a 370-ft depth for a total of 21 days. During this time they did extensive saturation diving and performed many useful tasks. An oil-well "Christmas tree" was placed at their 370-ft depth which the divers serviced under simulated operating conditions. The Christmas tree is a derrick-like structure supporting the wellhead. It is 8–10 ft in height and weighs approximately 5 tons. The main component of the wellhead is a large valve called the "McEvoy valve" which weighs 400 lb. Since the men did not have to fight their own weight, they were free to range unhindered in the vertical dimension as well as in the horizontal plane, and, since their tools weighed relatively less, by virtue of the buoyant forces, the McEvoy valve was replaced in less time underwater than had ever been done on dry land.

The sea surface remains the Archilles heel of all operations tried thereto, but with present undersea technology it can readily be sidestepped. A submersible, tailored to the needs of the oil industry, is now needed and can be designed utilizing the technology developed in the Sealab and the Conshelf projects. J. V. O'Neill et al. have patented a submarine design for performing all of the oil-well drilling operations while positioned on the ocean bottom, remaining unperturbed by surface weather phenomena (see Fig. 3).

Once the well has been "brought in," periodic service, maintenance, and repair could be accomplished from an oil-well service submarine. Such a submarine might be visualized as combining the advantages of the Sealab for extended stay at working depths with mobility for moving from harbors to drill site and/or from drill site to drill site. It would have a "lock-out" chamber to permit scuba or hookah divers free access to an from the sea and would maintain a helium-oxygen atmosphere at ambient pressure in the divers' quarters during oil-well servicing operations. Decompression could take place during return to port. Logistic support and/or crew replacement could be accomplished by having two such vehicles or by having a cargo submarine provide the necessary support. The submersible would require either a self-contained power source (possibly nuclear) or, for smaller vehicles, a hook-up with a service line dropped from a centrally located "FLIP"-type ship. This would permit periodic recharging of its batteries, during favorable sea-state conditions, while maintaining operational depths.

An offshore petroleum exploration, production, and transportation system could be made entirely invulnerable to adverse weather or ocean surface conditions. This system would combine the following subsystems: 1) service submarine to be used for a) seismograph exploration and b) service, repair, and maintenance of wellhead; 2) well-drilling submarine for a) drilling exploratory wells and b) drilling production wells; 3) Cargo submarine for a) providing logistic support and b) transporting personnel; and 4) tanker submarine or pipeline for transporting crude oil to refineries.

This system would eliminate the ocean bottom-to-surface section of the drill string and potentially could be designed for any depth, providing that all operations could be conducted from inside the submarines. In the interim, extravehicular saturation diving by aquanauts seems possible at depths of 600–1000 ft on the continental shelf, a mere 7% of which has been explored for petroleum to date. Eventually, the technology evolving from liquid breathing experiments may permit saturation diving at much greater depths.†

Table 3 Revenues of oil rig contractors

Oil-well drilling rig contractors	Revenues, $ × 10⁶ 1963	1964	1965	1966	1967	1968, Est.
Dixilyn Corp.	3.4	5.5	5.5	5.1	7.5	6.8
Global Marine	15.0	18.4	21.5	33.5	35.8	34.4
Ocean Drilling	10.7	14.0	18.2	22.6	28.2	31.2
Pike Corp.	52.9	55.1	53.5	59.4	63.0	67.8
Reading & Bates	17.7	21.2	19.5	31.1	36.3	34.0
Rimrock Tidelands	4.5	6.1	6.5	6.1	4.2	8.7
Santa Fe Drilling	60.7	51.3	65.0	83.4	86.9	104.5
Southeastern Drilling	13.9	13.4	15.5	26.8	35.4	38.8
Zapata Offshore	9.4	10.5	11.9	12.9	19.7	20.9
Totals	188.2	195.5	217.1	280.9	317.0	347.1

Offshore production of oil has reached a total of four million barrels a day and accounts for 15% of the free world's supply. The great unexplored potential of the continental shelves, coupled with the fact that most producing wells are only operating at a fraction of their potential, has led to forecasts that offshore oil production will catch up and surpass onshore output by the mid-1980's.

It has been conservatively estimated that the offshore reservoir holds at least 700 billion barrels of oil. Twenty countries are producing from underwater fields, most of which are located in the major producing areas such as the North Sea, Libya, Nigeria, the Middle East, Australia, Alaska, the Gulf of Mexico, and the U.S. Pacific coast, and many countries with excellent potential remain to be tested. Exploration is also continuing in the waters off Senegal, the Cameroons, Gabon, Surinam (South America), and Denmark.

A number of independent offshore drilling contractors own, operate, and contract out the use of their multimillion-dollar rigs to the major oil producers for use all over the world. These contractors own 150 mobile rigs worth over $600 million, whereas the 1970 fleet is expected to reach 200 units valued at more than $1 billion. The revenues derived from the leasing of these oil-well drilling rigs are shown in Table 3.

Offshore drilling costs are 3–5 times as high (depending on depth) as they are on land, but the higher success ratio (1 well in 4 is a producer offshore compared to 1 in 10 onshore) tends to offset the additional investment risk. At present, drilling rigs are in critically short supply, with every rig in the fleet hard at work. Therefore, opportunities undoubtedly exist for the imaginative combining of submersibles into economically competitive, integrated systems. These systems could offer oil producers substantial reductions in their operating costs as well as the unique advantages accruing from underwater or under-ice operations with service beyond the reach of adverse weather and unhindered by vulnerable links to the ocean surface.

The fish-protein resources of the world's oceans are receiving increased attention by many nations. Scientific methods of increasing the efficiency of fish harvesting techniques are actively being sought and found. The locating of large schools of fish by sonar, attraction by lights, luring and herding by electrical fields into the suction nozzles of large pumps, coupled with improved on-board processing and deep-freeze storing by large fishing factory-ships, has led to increased efficiency of the large Soviet marine fisheries fleet. Synthetic fibers have been used in making larger and stronger fishing nets and trawls. These have been studied extensively by the Japanese through underwater observations and have resulted in improved trawling techniques. Also, experimental fish farming has been carried on in Japan and elsewhere with very promising results.

† The following four paragraphs summarize pertinent information published in the March 10, 1967 special stock supplement of *Indicator Digest*, Indicator Digest Inc., Palisades Park, N.J.

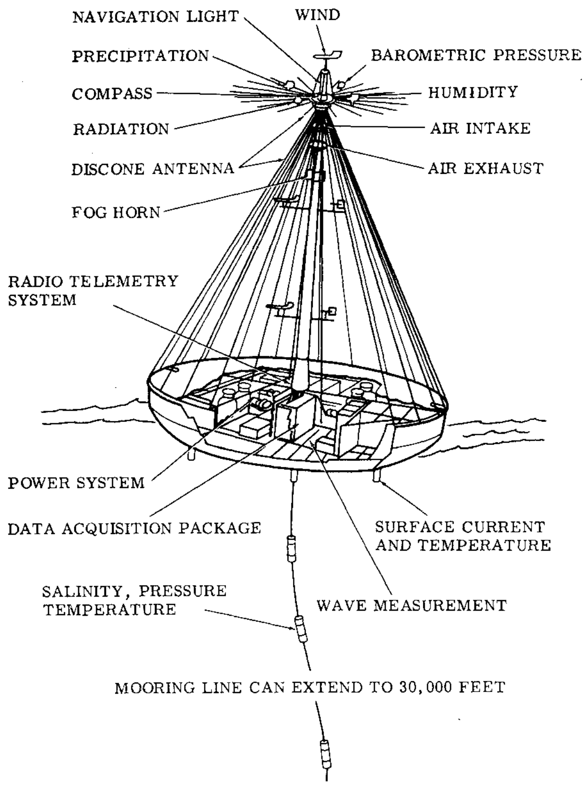

Fig. 4 General Dynamics/ONR ocean data station.

The U.S. fishing industry is composed mostly of small, uncoordinated groups. Neither they nor the government are willing to risk investing the necessary capital in research in order to develop the new tools and techniques required to remain competitive with their nationalized counterparts in Russia or Japan. Thus, within this country the new methods developed by other countries are being examined and our own new methods are being developed with somewhat less than the sense of urgency or financial support which should be required in response to world conditions, certainly far less than that required to attain an international leadership in this area.

The United States' interests in the food shortage and in particular the protein shortage, however, go beyond our own needs. The prevalent diseases affecting one-quarter of the earth's population are directly attributable to protein starvation, which is the leading cause of death in children between the end of weaning and 5 years of age.[1] Increasing populations are bringing about a crisis in the food problem. If our fishing industries were encouraged and given the right kind of governmental assistance and direction, they could aid tremendously in helping to meet the world's food requirements.

Other commercial underwater operations are at present in rather an embryonic stage. It is difficult to foresee how long a period of relative latency will be required before their growth reaches sizable proportions. Obviously, the exploitation of underwater mineral resources other than petroleum, and sulfur or gas, will depend on exploration by submarine-borne geologists with the capability to examine specimens and formations while on the sea floor. The vehicles required are similar to those proposed for offshore underwater oil-well service applications. It is relatively easier to train geologists as scuba divers than vice versa. Similarly, salvage of sunken ships, both ancient and recent, can be accomplished at depths to almost 1000 ft with essentially the same type of submersible providing a mobile underwater base for "saturation" divers. This would be considerably more efficient than present techniques.

An undersea pleasure craft industry is a distinct possibility. At present, recreational use of the ocean supports a 2–4 billion dollar industry in the U.S. alone. Of the 3 million people directly interested in diving, there are 1 million active amateur divers using either snorkels or scuba and skin-diving gear. Probably with proper promotional techniques this potential customer base could be expanded into a market of sizable proportions consisting of those interested in buying more sophisticated types of gear and vehicles. A small glass-sphere, pressure-vessel submersible[11] could provide a versatile, safe vehicle for exploring the wonders of the sea in three dimensions.

Marine Technology—State-of-the-Art

Buoys

Surface ships have been used for centuries as drifting observation platforms, sometimes by design and at other times by the force of circumstances. The floating logs, rafts of the Kontiki class, sailing ships, and more recently freely drifting ships of the Indian Ocean expedition have measured the surface currents of the oceans and associated weather conditions, the sophistication of measurement varying as a function of the technological era in which they evolved.

Weather data are needed over a wide range of horizontal and vertical grid scales to establish the order necessary for prediction purposes within this highly complex field of interacting media. Commercial aircraft frequently transmit in-route weather data to appropriate weather data collection stations. These data are of considerable use in establishing weather patterns and pinpointing unusual disturbances in remote areas. Increasingly, satellites are providing accurate large-scale pictures of the world weather situation.

Similarly, the tremendous need for oceanographic and atmospheric data near the surface has led to utilizing merchant ships for gathering data along the course of their regular travels. Although the data are somewhat arbitrary as to their sampling location, i.e., along the trade routes which try to avoid bad weather, they still help to fill the knowledge gap. Vertical fluxes of heat, momentum, and water vapor must be determined in order to predict large-scale atmospheric behavior for periods longer than 48 hr. This requires a carefully planned and coordinated collection of data by means of fixed platforms, buoys, and submarines, rather than hit-or-miss random samplings, in order to obtain meaningful results. Buoys are a critical link in the data collection chain since in many cases they are positioned on the highly sensitive air-sea interface.

There are a number of different types of buoys suitable for a variety of purposes. They may be classified as to 1) types of mooring, a) bottom moored, b) drifting with submerged drogue, c) freely drifting and 2) depth locations of buoys, a) surface, b) intermediate depth, c) bottom. In addition, they may be classified as manned or unmanned and as to function, type of equipment used, or type and manner of data transmission.

During the early stages of development of buoy technology, special-purpose buoys were developed which either served as markers for channels, obstacles, fish traps, etc. or which measured only a limited number of parameters (e.g., temperature, salinity, current velocity). The Navy Oceanographic and Meteorological Automatic Device (NOMAD), although an order of magnitude more sophisticated than earlier buoys, was limited to the transmission of meteorological data. By utilizing a 60-w nuclear generator, it was capable of unattended operation for up to six months and was used to warn of approaching storms.

The Ocean Data Station[12] developed by the Office of Naval Research and the Convair Division of General Dynamics is a significant step towards furthering buoy technology (Fig. 4). This unmanned, 50,000-lb, 40-ft-diam, 7-ft-thick, discus-shaped buoy is capable of withstanding 60-ft waves, 150-knot winds, 10-knot currents, and may be moored in depths to

30,000 ft by its 2-in.-diam nylon cable. A variety of sensors are located on its 38-ft antenna mast, within its hull, and are distributed at intervals along its mooring line. Thus, a wide range of oceanographic/weather data are gathered, stored, and transmitted over its high-frequency channels every 6 hr on command from a shore station located up to 3000 miles away.

The Ocean Data Station is designed for one year's unattended operation; however, its conventional propane-powered generator system carries a two-year fuel supply. Buoys of this type appropriately spaced could provide synoptic data on weather conditions, air-sea interactions, ocean currents, deep-ocean tides, animal migrations, and other phenomena of interest to the weather forecasting service, scientific researchers, the fishing industry, and the Navy's Antisubmarine Warfare Environmental Prediction Systems (ASWEPS).

The National Oceanographic Data Center (NODC) was established in 1961 to acquire data from all of the aforementioned and additional sources including those of foreign countries. After suitable processing, these data are stored for future reference and are disseminated throughout the oceanographic, scientific, commercial, and military communities for their many uses. The Presidential Panel on Oceanography recommended increased funding so as to extend the scope of this valuable service.[1]

The required buoy and sensor technology, submersibles as underwater sensors, satellite sensors or relay subsystems, and efficient data handling-distribution subsystems are ready for expansion. The need exists for a completely coordinated environmental sensing, sampling, measuring, and, therefrom, analysis and prediction system. What remains is the necessary financing, organizing, and sense of urgency required to fill this need with its resulting step forward.

FORDS-FLIP-SPAR-STOP

The analysis and prediction of oceanic acoustic properties is the subject of intense research by the Navy in support of its submarine detection efforts. Four somewhat similar concepts have been developed to provide the unusually stable floating platforms necessary to perform precise measurements of sound waves at depths to 300 ft. All four concepts require a large proportion of the weight of the float to be submerged, thereby providing a stable platform in heavy seas.

The Floating Ocean Research and Development Station (FORDS) concept developed by the Naval Research Laboratory envisions a 300-ft manned, floating, vertical tower, 250 ft of which would extend below the surface.[13] The tower would be towed in an upright position on a barge to the emplacement site, but thereafter would be self-sufficient for up to four weeks since it would contain its own fuel, power, and housekeeping facilities. The station would be used in the evaluation of acoustic transducer design and has the added capability of being able to lift a 900,000-lb load and lower it to a depth of 5000 ft.

Similarly, the Floating Instrument Platform (FLIP) developed by the Scripps Institution of Oceanography for the Office of Naval Research[14] and the Seagoing Platform for Acoustic Research (SPAR) developed by the Naval Ordnance Laboratory[15] are primarily intended for acoustic research and are emplaced in a vertical position (50 ft above/300 ft below the surface). However, FLIP and SPAR are towed in a horizontal attitude and by the flooding of tanks flip to the vertical position at the emplacement site. Blowing of ballast tanks by compressed air with the subsequent return to a horizontal attitude readily permits redeployment. FLIP is self-sufficient for up to two weeks and provides living quarters for four people. The unmanned SPAR is controlled and receives its power via a 3000-ft umbilical electrical cord to a mother ship.

The Stable Ocean Platform (STOP) concept[16] is an advanced FLIP-type ship that has been proposed as a platform for tracking spacecraft from remote ocean areas as part of the global tracking network. Alternate usages could include incorporation into the early warning system, weather data collection, or even as a missile launching platform. It would maintain its position either by a mooring system or dynamic positioning (e.g., the MOHOLE platform, see the following subsection).

All four platforms rise and fall less than 3 ft with a 1° side-to-side maximum oscillation in a heavy sea (30-ft waves) and negligible movement in normal seas. The future application of these exceptionally stable platforms, which can safely ride out hurricanes and heavy seas, may be particularly useful not only for acoustic research and tracking, but possibly for other uses such as offshore oil drilling operations. The FLIP ship, with its ease of deployment and redeployment, adds a new operational module which may well provide a springboard to more advanced concepts aimed at solving existing problems.

Offshore and Deep-Water Platforms

The increasing rate of oil consumption throughout the world, coupled with the increasing difficulty of locating major new reserves on the extensively probed continents, has pushed the search for oil to the shallow waters of the continental shelves and has even now led to developmental techniques for eventual use at open ocean depths. There has been a particularly close cooperation and exchange of ideas between the government and the petroleum industry with the result that a number of innovations have significantly advanced undersea drilling technology in recent years.

During the 1930's, inshore areas and marshes of the Gulf of Mexico and Lake Maracaibo were exploited by mounting conventional drilling equipment on fixed wooden pile-supported structures and floating barges. Operational water depths of 6 ft were typical of this period. These early marine drilling efforts were followed by steel and reinforced concrete pile-supported platforms of relatively small size (40 ft × 80 ft) for operation 20 ft above the surface in 80 ft of water. Converted naval craft tended the platforms and supplied power, pumps, and mud tanks, as well as accommodations for the crew during drilling operations. At present, there are 90 tender/platform combinations of this type in operation. The tenders are now especially designed for this task and include helicopter pads for rotating crews and transferring some supplies. This combination can drill 20,000-ft holes in up to 200 ft of water.

One out of four wells is a producer of oil; thus, of necessity, semimobile drilling platforms evolved for exploratory work. Some were merely rigs that had the ability to float and could be towed to the drilling location. Upon arrival, flooding of the buoyancy tanks and structural members caused the tower-supported platform to settle in such a way that the legs rested on the ocean bottom. A similar type was a barge, the retractable legs of which were lowered to the sea floor, thus permitting the barge-platform to jack itself up for wave clearance.[17]

Floating, semisubmerged types of platforms have been developed for use in deeper water. The bulk of the weight is beneath the surface, resulting in a relatively stable base for the platform which is 30–70 ft above the surface. Position is maintained using conventional anchors. Increasing depths require bigger anchors; thus as many as nine 30,000-lb anchors are used for station keeping in 600-ft depths of water.

Concurrently, drill ships are being developed for operations in even deeper water. A catamaran-type hull has been used for the drill ship "E. W. Thornton." The advantages of greater stability, less heel, and better position holding capabilities, compared to conventional hull types, make the catamaran very attractive for use as an oil drilling platform.

Particularly important has been the success attained by the group composed of the Continental, Union, Superior, and

Table 4 Costs of offshore oil rigs

Type of rig	Drilling depth in water, ft	Cost of rig, $
Fixed platform (self-contained)	100	500,000
Dynamic positioning (floating)	1,000	5,000,000
Dynamic positioning (floating)	10,000	50,000,000

Shell Oil companies who converted a YFNB Navy barge into the drilling ship CUSS I. This unique ship with its dynamic positioning capabilities was used for drilling in water depths of 1500 ft at rates of 450 ft/day and has demonstrated its unusual mobility by changing from one hole to another in less than a single day.[18]

In 1961, CUSS I was contracted to the National Science Foundation (NSF) for testing preliminary cores in ocean depths never before attempted. The MOHOLE project,[19] using a dynamically positioned, semisubmerged floating platform was, prior to its cancellation, seeking answers to some of the most important scientific questions of our time: 1) How old is the earth? 2) What is its origin? 3) Is it getting hotter? 4) How did life begin on earth? 5) How old are the ocean basins? 6) How did they get filled with water? and 7) Why do they differ from the continents? At present, many theories about the earth are based on studies of less than 1% of its volume and 30% of its surface, hence the desperate need for supporting data and in the case of contradictory data, revision and updating as required.

The aim of the NSF-supported MOHOLE project was to drill a hole 30,000 ft below sea level in 15,000 ft of water north of the Hawaiian island of Maui. This penetration was to have gone through the "Mohorovicic Discontinuity" which marks the boundary between the earth's crust and the mantle. Thus, by direct sampling of the mantle, which makes up 85% of the volume of the earth, data were to have been sought extending 2 billion years backwards in time and would possibly have led to answers for the preceding questions. Indeed, preliminary drilling in 11,700 ft of water off Guadalupe Island near southern California by CUSS I has already required the revision of existing geological theories. New data have shown the internal temperatures of the earth to be higher than expected and the seismic velocity in the upper layer of the earth's crust to be 1.6 km/sec slower than previously estimated.

The drilling platform for MOHOLE was designed to stay within a 400-ft radius of its center position so as not to exceed the allowable stresses of the 30,000-ft drill string. This was to have been achieved by a dynamic positioning system which senses the platform's position by sonar and radar reflections from a series of bottom-anchored, taut-line subsurface and surface buoys, respectively. An onboard analog computer digests the bits of position information which, through appropriate displays and an integrated control, commands six vertical-axis, variable-pitch underwater propellers to generate the forces necessary for the platform to maintain an optimum position for a period of up to three years in the face of prevailing winds, currents, and weather.[20]

Unfortunately, politics and rising costs forced the cancellation of the MOHOLE project prior to the achievement of its ambitious goals. In spite of this, it went a long way toward proving the feasibility of the associated drilling concept which will, with modifications, continue to be utilized by the petroleum industry for probing the ocean's depths. This concept has thus gone full circle back to its originators.

Drilling in depths of water two orders of magnitude deeper than two decades ago has been achieved by a corresponding increase in drilling rig costs, also by two orders of magnitude. Typical oil-rig costs for drilling an oil well in various water depths are shown in Table 4.

An oil-well rig for drilling on land costs about $150,000 by way of comparison. However, the higher cost for the offshore platforms are justified by their higher ratio of successful producing wells ($\frac{1}{4}$ compared to $\frac{1}{10}$). In general, mobile platforms are higher in original cost but since self-contained, fixed platforms are difficult to salvage and impossible to move intact, reusable mobile platforms are especially advantageous for exploratory work to find out quickly whether a lease is commercially productive or not.

The costs of leasing mobile rigs from drilling-rig contractors are given in Table 5 for units which are anchored conventionally instead of dynamically positioned. Also shown are 150-ft water drilling depth fixed platforms, self-contained and with tender.

The costs shown in Tables 4 and 5 are typical of platforms operating in relatively calm waters such as the Gulf of Mexico. When weather conditions are typically more severe, e.g., the Pacific coastal waters off California, then costs begin to multiply rapidly. The ice-floe conditions in the Cook Inlet of Alaska multiply costs tenfold. A fixed platform there in 100 ft of water costs $5 million.

Thus, drilling costs are increasing as greater water depths in areas of unfavorable weather and ocean surface conditions are encountered. This will eventually require that well drilling and completion systems be emplaced on the ocean floor with servicing by submarines. The economic situation will spur the necessary technological advances.

Although the continental shelves will probably provide enough territory for exploitation in the near future, only the vast reaches of open oceans will sustain the petroleum demands of developing countries, increasing world populations, advancing technologies, and aggressive international oil diplomacy.[21]

Diving

The familiar "hard-hat," canvas-suit, heavy-breastplate, conventional diving suit was developed in 1837. With minor modifications, it has been in use until recently, but the much more efficient scuba (self-contained underwater breathing apparatus) and hookah equipment are in the process of taking its place.[22] Safe and relatively inexpensive scuba gear has captured the fancy of the public and has turned shallow scuba diving into somewhat of a national pastime.

Scuba divers, by eliminating the umbilical life line/air hose and by relying on a portable back pack of oxygen/helium, can operate unhindered at depths never before possible. The hard-hat diver, breathing normal air as supplied conventionally, becomes unable to perform simple tasks at 200-ft depths and reaches his limit at 300 ft. If he were to continue to a depth of 350 ft, he would lose consciousness. The narcotic effects of oxygen/nitrogen under pressure become lethal at this depth. The conversion to a predominantly helium breathing atmosphere with some nitrogen and oxygen alleviates this problem considerably and will probably permit dives to 1000 ft with very little impairment of the diver's faculties.

It seems that the lower the molecular weight of the gas breathed by the diver, the greater the depth which he can reach before the narcotic effects of the gas become noticeable.[23] From this standpoint, a hydrogen/oxygen mixture would be ideal if it were not for the explosive potential of the mixture. The Swedish engineer, Arne Zetterstrom,[24] using this mixture, was able to descend to a depth of 525 ft as early as 1945.

Table 5 Rental costs of offshore oil rigs

Type of rig	Drilling depth in water, ft	Rental cost, $/day
Fixed platform (self-contained)	150	3000
Fixed platform with tender	150	4200
Mobile rigs	100	6000
Mobile rigs	150	7500
Mobile rigs	250	8500

The U.S. Navy's Man-in-the-Sea concept, which has evolved through the Sealab I and II experiments, has successfully placed men in a steel chamber in 200 ft of water at ambient pressure breathing in 85% helium, 11% nitrogen, and 4% oxygen mixture for up to $6\frac{1}{2}$ weeks.[25] The Sealab aquanauts used scuba gear to take dives from their laboratory/living quarters and demonstrated their abilities to perform useful tasks for relatively long periods of time. Their excursions only needed interruption for changing helium/oxygen tanks as the supplies became depleted. Also, it was found that short "bounce dives" could be made to 300-ft depths without the need for decompression to return to the 200-ft level.

This technique of staying at working pressure between dives permits decompression time to be amortized over an extended period so that a scuba diver may put in an 8-hr diving day with no decompression time. The decompression penalty of a few days is paid for only at the end of the work schedule, which could conceivably last anytime up to 3 months or longer.

The feasibility of extended undersea diving operations has thereby been amply demonstrated. Useful work was accomplished at these depths on a routine basis and shows clearly a definite commercial potential.

This potential is being exploited by a number of companies presently servicing dams, doing salvage work, and repairing ships in situ, etc., but, for the immediate future, they have set themselves the goal of working at 600–1000-ft depths in support of offshore oil production.[26]

Conclusion

Many individuals and groups within various companies and governmental agencies are continuing research into a large number of areas directly or indirectly connected with oceanographic activities. Environmental analysis is yielding increasingly more accurate and longer-range predictions as well as control in some instances. Mathematical models (exact and empirical) combined with new computers are providing powerful methods for mission and system analyses. In addition, new subsystems (e.g., nuclear power, scuba, dynamic positioning, etc.) and new or improved materials are extending vehicle system capabilities by orders of magnitude, thereby permitting missions only dreamed of heretofore.

The gathering of small grid scale (5–10 km) oceanographic and weather data in selected areas from a system of buoys is possible using state-of-the-art components. These data are vitally needed before the dynamics of oceanographic processes can be accurately analyzed or before long-range environmental predictions can be attempted. Environmental analysis, by providing model environments and probability assessments of what and how frequently extreme conditions will be encountered in various regions, would be particularly valuable in both military and commercial operations.

The use of new materials may readily facilitate the extension of undersea activities to much greater depths with glass and glass ceramics as prime contenders for use as deep submersible hull materials and ocean bottom emplaced structures. Considerable pioneering work needs to be done in this area to solve the design problems of applying these materials so as to develop their full potential.

New subsystems, in particular the application of nuclear power to cargo/tanker submarines, can provide tremendous potential for the achievement of homesteading, military, and commercial missions of inestimable importance.

In conclusion, it may be stated that oceanographic activities require support across the board in order to fulfill this nation's military and geopolitical obligations as well as to remain commercially viable and competitive in the rapidly changing technological environment. There are indications that we are falling behind in many areas, fishing, large oceanic vehicles, and the applications of nuclear energy to name a few. Increased research efforts and their application to vehicle technology, system and mission analyses combined with the full utilization of present technology to increase further the scope and accuracy of environmental analysis, can provide the springboard for new and vastly improved systems for the benefit of all.

References

[1] "Effective Use of the Sea," Report of the Panel on Oceanography, President's Science Advisory Committee, June 1966, U.S. Government Printing Office, Washington, D.C.

[2] Bulban, E. J., "Gemini Program Concludes with Display of Long-Term EVA Capability," *Aviation Week and Space Technology*, Vol. 85, No. 21, Nov. 21, 1966, pp. 26–29.

[3] Carpenter, M. S., "Man in Space and Man in the Sea," *Astronautics & Aeronautics*, Vol. 4, No. 4, April 1966, pp. 32–35.

[4] Stambler, I., *The Battle for Inner Space*, 1st ed., St. Martin's Press, New York, 1962, p. 26.

[5] Terry, R. D., *The Deep Submersible*, 2nd ed., Western Periodicals Co., North Hollywood, Calif., 1966, p. 72.

[6] Stachiw, J. W. and Snyder, R. F., "The Design and Fabrication of Glass and Ceramic Deep-Submergence, Free-Diving Instrumentation Capsules with Capabilities of 3500 Fathoms," Preprint 65-UNT-1, Underwater Technology Conference, The American Society of Mechanical Engineers, New London, Conn., May 1965.

[7] Perry, H. A., "The Argument for Glass Submersibles," *Undersea Technology*, Vol. 5, No. 9, Sept. 1964, pp. 31–35.

[8] Trumbell, J. et al., "An Introduction to the Geology and Mineral Resources of the Continental Shelves of the Americas," Geological Survey Bulletin 1067, 1958, U.S. Government Printing Office, Washington, D.C.

[9] Stephan, E. C. and Link, E. A., "Routine Man-in-the-Sea Commercial Operation is Aim of New Company," *Undersea Technology*, Vol. 6, No. 3, March 1965, pp. 20–22.

[10] "Marine Contracting, Inc. Dives for Profit," *Marine Engineering/Log*, Vol. 71, No. 2, Feb. 1966, pp. 57 and 100.

[11] McLean, W. B., "Future Exploration of the Ocean," *Astronautics & Aeronautics*, Vol. 4, No. 7, July 1966, pp. 74–76.

[12] "The First Ocean Data Station," *Naval Research Reviews*, Vol. 17, No. 10, Oct. 1964, pp. 1–7.

[13] Faires, R. E., "FORDS—Floating Ocean Research and Development Station," *Naval Research Reviews*, Vol. 15, No. 12, Dec. 1962, pp. 4–11.

[14] Bronson, E. D. and Glosten, L. R., "FLIP—Floating Instrument Platform," SIO Ref. 62-24, Nov. 1962, Scripps Inst. of Oceanography, Univ. of California, San Diego, Calif.

[15] "Seagoing Platform for Acoustic Research," *Naval Research Reviews*, Vol. 17, No. 10, Oct. 1964, pp. 8–11, and 28.

[16] STOP—Ocean Platform with a Brain," *Marine Engineering/Log*, Vol. 68, No. 5, May 1963, p. 58.

[17] Pratt, W. and Roy, W. A., "Off-Shore Drilling Barges," *International Shipbuilding Progress*, Vol. 7, No. 76, Dec. 1960, pp. 510–522.

[18] "New Off-Shore Drilling Techniques," *Marine Engineering/Log*, Vol. 62, No. 13, Dec. 1957, p. 83.

[19] Bascom, W., *Hole in the Bottom of the Sea*, 1st ed., Doubleday, Garden City, 1961.

[20] Bladen, D. H., "Dynamic Positioning for Deep Drilling," *Marine Engineering/Log*, Vol. 65, No. 6, June 1960, pp. 68–69.

[21] Zerfoss, A. B., "Dilemma in Oil," *U.S. Naval Institute Proceedings*, Vol. 90, 2, Feb. 1964, pp. 52–63.

[22] Goff, L. G., "Self-Contained Diving and Underwater Swimming," *Naval Research Reviews*, Vol. 10, No. 9, Sept. 1967, pp. 14–19.

[23] Blockwick, T. H., "Breathing Media in Deep Sea Diving," *Journal of the American Society of Naval Engineers*, Vol. 68, No. 2, May 1956, pp. 327–330.

[24] Searle, W. F., Jr., "A History of Man's Deep Submergence," *U.S. Naval Institute Proceedings*, Vol. 92, No. 3, March 1966, pp. 80–92.

[25] Groves, D., "Sealab I," *U.S. Naval Institute Proceedings*, Vol. 91, No. 2, Feb. 1965, pp. 64–71.

[26] "The Modern Diver," *Journal of the American Society of Naval Engineers*, Vol. 73, No. 2, May 1961, pp. 377–379.