Manned Submersibles for Research

These immature but developing tools open another door for examining history and current processes.

Henry A. Arnold

The legendary descent of Alexander the Great in a "glass barrel" in 323 B.C. to "see what there was and to defy the whale" establishes him as a contender for the earliest user of a submersible for scientific purposes (*1*); but his report, which stated that he saw a fish so large that it took 3 days to swim past, gives more justification for classifying him as a forerunner of today's fisherman. Since the time of Alexander, submerged vehicles and divers have been used occasionally for commercial purposes, but principally they are used for military purposes. With few exceptions such as the tethered spheres of Beebe and Barton, deep exploration for serious scientific purposes awaited the development of the bathyscaph and the dives of Houot, Willm, and the Piccards in the early 1950's.

Led by R. Dietz of the Office of Naval Research, the U.S. Navy entered this untracked field by chartering Piccard's *Trieste I* in 1957 and then purchasing it in 1958. The bathyscaph was assigned to the Navy Electronics Laboratory in San Diego and thus became the first submersible owned by the United States for deep research. By 1960, the Navy had dived the *Trieste* 35,800 feet (10740 m) to the bottom of the Challenger Deep off Guam and proved that fish live at the deepest known spot in the oceans.

From 1959 to the present, U.S. Navy officers and scientists from Scripps Institution of Oceanography and the U.S. Navy Electronics Laboratory have pursued an active program, using *Trieste I, Trieste II*, the Cousteau *Saucer* (*SP 300*) and the Westinghouse *Deep Star 4000* to establish the San Diego area as a world center for the use of submersibles for research. The vision of pioneers such as the Piccards and Cousteau, and the steadfast encouragement of a few U.S. scientists, such as Allyn Vine and A. B. Rechnitzer, provided a principal impetus for the decade of development.

The first systematic design of a U.S. research submersible was developed in the summer of 1958 when Wenk, DeHart, Mandel, and Kissinger, working to the scientific requirements of U.S. oceanographers, developed the concept and analysis of a deep-diving oceanographic research submersible with an aluminum hull (*2*). Still, despite the strong recommendation of the landmark report of the National Academy of Science Committee on Oceanography (*3*), no submersibles for research were built in the United States until 1961.

Figure 1 shows the numbers completed each year since then. Much recent activity and technical progress can be attributed to the Navy's Deep Submergence Systems Program (*4*), an outgrowth of the difficulty of finding and examining the sunken submarine *Thresher* in 1963, which stimulated and encouraged an eager, but cautious industry interest. Nevertheless, in its report *Oceanography 1966* (*5*), the National Academy of Sciences Committee on Oceanography states "repeated customer surveys have shown that the small two- or three-man submersible is a logical craft for research and that several more of these simple reliable craft need to be built."

The capabilities, limitations, characteristics, and use of the small, manned submersible craft employed in increasing numbers for research in the United States in the past 5 years are discussed in this article. Discussion of military submarines, tethered vehicles, whether manned or unmanned, and those few craft engaged in research in other countries, has been omitted.

The bathyscaph and some of the other small manned craft can dive deeper than large military submarines and there is a tendency to speak of them as "deep research vehicles" (DRV); however, this raises the questions: "How deep is deep?" and "does a 600-foot (180-m) maximum depth vehicle qualify?". In my view these distinctions are not significant—there is much scientific and other work yet to be done on the continental shelf. Figure 2 illustrates some other ways of classifying submersibles. The term "research submersible" (RS) is used here to designate any small manned untethered vehicle designed or used for research.

General Description

Present technology does not permit large deep-diving submersibles. For this and reasons of economy, the research submersible is usually small, which allows it to go to relatively deep depths and also to maneuver safely within a few feet of the bottom or of some other solid object that is to be observed. Viewing ports—the more the better—are highly desirable if not essential. Only a few knots of forward speed, an endurance of 8 hours or so, and several hundred pounds of instruments, cameras, lights, sensors, and data recorders, are necessary. The introduction of fuel cells and small nuclear reactors is not far off. When the mission justifies the costs, these new power sources will allow a major gain in submerged range, speed, and endurance which, in turn, will permit extended search and exploration of the oceans. A pamphlet published by the Interagency Committee on Oceanography in 1965 contains an excellent description of research submersibles as of that date (*6*).

Two other categories of small submersibles will soon appear in increasing numbers. The "submersible work boat" will have many of the same characteristics as the research submersible, but, instead of a full load of instruments or sensors, it will carry heavy manipulators, earth-moving equipment, and devices for lifting and for holding its position, as well as welding, cutting,

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and other tools. It will need more power for doing the work. Small submersibles for recreation might become popular. They will need less depth capability, but must be inexpensive and safe. Perhaps there is also a fourth category—one that is readily traceable to the interest of E. A. Link. The *PL4* submersible, developed jointly by Link and J. Perry this year, carries divers to the desired location and depth and allows them to leave and reenter the submersible at any depth down to 600 feet (180 m). This lockout feature can be incorporated in the other categories if the weight budget will permit.

Table 1 lists the names and principal characteristics of some of the better-known small submersibles which have been used for research in the United States in the past 5 years. Table 2 lists others now being built.

Direct Observation: A Primary Advantage

The unique advantages of the manned submersible for research and exploration start with its capability of taking a scientist to the site of his observations or experiments, even though the environment is hostile or distant. Experience has shown that, despite the existence of sophisticated instrumentation, the presence of man with his versatile and flexible senses serves the needs of scientific observation and exploration best. Television cameras in sufficient numbers and quality to duplicate man's field of vision, plus stereo and color perception —and all with a real time transmission and feedback from deep depths —may be technically possible but almost certainly will be prohibitive in terms of weight, volume, cost, and freedom of action.

Within his physiological limits, man can go under water to observe and collect as an individual exposed diver, wearing only a light protective suit and equipped with underwater breathing apparatus. But where the distance, pressure, temperature, or other hostile factors exceed his physiological endurance, he needs the support of a pressure-proof capsule. Thus protected he sacrifices manual dexterity, maneuverability, access to restricted areas, and the ability to use tactile senses, but gains greater mobility, endurance, carrying capacity, and relative comfort for his observations.

Other Unique Capabilities and Limitations

Contrary to a surface ship, the free-running submersible is decoupled from the motion of the sea surface. For placing objects precisely on the bottom, for making gravity measurements, or for floating with a current at depth—this is a unique advantage. Even a body tethered to a surface ship by a long towing and transmission cable responds to the wave-induced perturbations at the upper end of the cable (F. Spiess of Scripps reports approximately a 50 percent response at the end of a 25,000-foot long catenary); and the tethered body cannot be as responsive as a free submersible when sharp turns or other quick motion changes are desired for investigation or similar purposes.

On the other hand, the manned submersible has some fundamental disadvantages and limitations. Being small and with short range, it must be carried or towed to the site of the dive. It cannot operate in heavy seas (greater than sea state 2 or 3 for most contemporary vehicles) because of the dangers associated with launching or recovering when the submersible and the support ship are responding differently to the waves. Experience shows

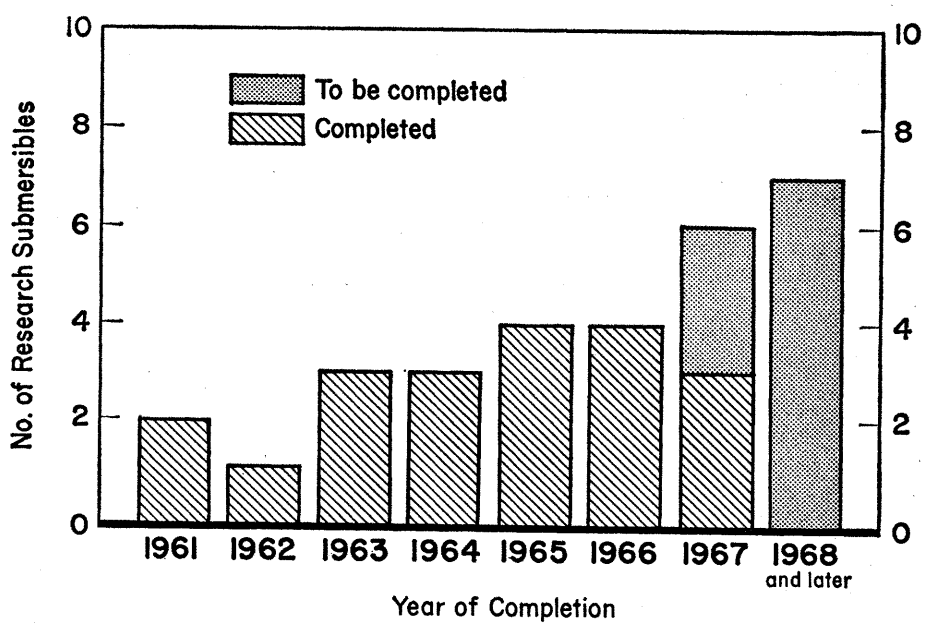

Fig. 1. Number of research submersibles built in the United States (see Tables 1 and 2).

Type	Manned	Unmanned
	Tethered	
1. Towed	Atlanta I (U.S.S.R.)	Towed sonar or instrument package
2. Suspended	Beebe's bathysphere	"Mobot" (Shell Oil Co. device for completing well heads)
3. Self-propelled	None known	Controlled underwater recovery vehicle ("CURV")
4. Bottom crawling	None known	Remote underwater manipulator (RUM)
	Untethered	
1. Predominately vertical path	Bathyscaph	Expendable bathythermograph
2. Predominately horizontal path	"Auguste Piccard" large military submarine	Torpedo
3. Vertical and horizontal path	"Aluminaut", "Alvin" Other	Instrumented torpedo (University of Washington)

Fig. 2. Submersible craft can be classified in various ways. This method highlights some gaps in the present spectrum.

Table 1. Characteristics of some submersibles that have been used for research. Abbreviation: kt, knot.

Name and date of completion	Operating depth (ft)	Propulsion endurance	Length (ft)	Weight in air (lb)	Crew/passengers	Payload (lb)
	Reynolds International Inc.					
Aluminaut 1965	15,000*	32 hr at 2.5 kt	51	146,400	3/4	6,000
	ONR, Woods Hole Oceanographic Institution					
Alvin 1965	6,000	8 hr at 1.6 kt	22	29,200	1/2	900
	American Submarine Co.					
Sportsman 300 1961	300	3 hr at 3 kt	13	2,000	2	450
Sportsman 600 1963	600	6 hr at 3 kt	13	3,500	2	750
	University of Pennsylvania					
Ashera 1964	600	10 hr at 1 kt	17	8,600	1/1	175
	Lear Siegler Inc.					
Benthos V 1963	600	2 hr at 2 kt	11.3	4,200	1/1	400
	Naval Ordnance Test Station					
Deep Jeep 1964	2,000	4 hr at 2 kt	10	8,000	1/1	200
	Lockheed Aircraft Corporation					
Deep Quest 1967	8,000	24 hr at 2 kt	40	116,480	2/2	3,400
	Westinghouse Electric Corp.					
Deep Star 4000 1966	4,000	5–10 hr at 1 kt	18	18,534	1/2	820
	Marine Technology Inc.					
Paulo I 1967	600	10 hr at 3 kt	13.5	6,025	1/1	480
	Perry Submarine Builders, Inc. and Ocean Systems Inc.					
PC3-A 1962	300	8 hr at 2 kt	19	5,325	1/1	750
PC3-B 1964	600	10 hr at 1.25 kt	22	6,050	1/1	500
Deep Diver PL4 1967	1,350	15 hr at 1 kt	22	16,500	1/3	1,200
	General Dynamics Corp./Electric Boat Co.					
Star II 1966	600	8 hr at 1 kt	17.8	9,400	1/1	250
Star III 1965	2,000	4 hr at 3 kt	24.5	20,000	1/1	1,000
	Hydro Tech. Co.					
Submaray 1961	300	5–6 hr at i.s.†	13.6	3,200	1/1	150
	U.S. Naval Ordnance Test Station COMSUBPAC					
Trieste II 1965	20,000	5 hr at 2 kt	67	440,000‡	1/1	20,000
	Submanaut Enterprises					
Submanaut§ 1959	300	20 hr at 3 kt	43	100,000	2/4	4,500

* Design depth. † Intermittent speed. ‡ Displacement. § No research work.

Table 2. Characteristics of submersibles that are being built. Abbreviation: kt, knot.

Name and date of completion	Operating depth (ft)	Propulsion endurance	Length (ft)	Weight in air (lb)	Crew/passengers	Payload (lb)
		U.S. Navy				
Autec I 1968	6,500	8 hr at 2 kt	22	29,200	2/1	900
Alvin II 1968	6,500	8 hr at 2 kt	22	29,200	2/1	900
		General Motors				
Dowb 1967	6,500	26 hr at 1 kt	16	14,274	2	1,020
		Westinghouse Electric Corp.				
Deep Star 2000 1968	2,000	8 hr at 2 kt	14	8,000	2	400–1,000
Deep Star 20000 1969	20,000					
		North American Aviation				
Beaver 1968	20,000	12 hr at 2.5 kt	25	27,000	2/4	2,000
		Grumman Aircraft Engineering Grp				
PX-15 1967	2,000		48.6	240,000	5–6	5,700
		U.S. Navy				
NR-1 1969					5/2	
		Perry Submarine Builders, Inc.				
PC4-B 1968	600	6 hr at 2 kt	25	165,550		2,000
PC5-B 1967	1,200	8 hr at 1½ kt	15½	7,300	3	500

that about 15 percent of the operating days otherwise available in U.S. waters (except Alaskan) will be lost because of the weather. In almost all of the present submersibles the scientist looking out of viewports must remain in an awkward position. As compared to an unmanned vehicle, the payload available for instruments is lower and the original cost must be higher to provide for safety features, life support, higher reliability of the vital systems, and hence more testing. For simple routine tasks, the tethered unmanned vehicle undoubtedly has a lower first cost and should be used whenever the task permits.

Instrumentation

As for many other kinds of scientific observation, the human eye is a principal instrument for the research submersible. Other standard oceanographic instruments adapted and used include: reversing thermometers, temperature probes, salinometers, current meters, bathometers, magnetometers, gravimeters, velocity meters, plankton nets, sonars, hydrophones, transponders, reflectance plaques, densitometers, cameras, and strobe lights. External manipulating arms and a growing list of special instrumentation such as dye cakes and a "slurper" for collecting biology specimens have also been used but most need further development. Figure 3 (top) shows the *Deep Star 4000* with an ingenious "brow" on which several of these instruments are mounted. To assist in balancing the weight and longitudinal moment, syntactic foam blocks with a density of about 40 pounds per cubic foot (640 kg/m^2) have been attached at each side of the brow (7).

Payload

When trimmed for neutral buoyancy, the total weight of the research submersible must equal the weight of the water it displaces so that there is no net vertical force. After an adequate hull, machinery plant, other equipment, and crew needed for operating the boat has been provided, whatever difference between displacement and weight remains can be allotted to people and instruments for research. In most research submersibles, as in all high-performance craft, the weight available for payload is small. For a given hull material, the deeper the maximum operating depth, the smaller the percentage of total weight which remains for the payload (Fig. 4). For very shallow diving boats, other factors may overshadow the relation between payload and depth of predicted collapse of the hull. As materials for pressure hulls, with higher ratios of strength to weight become technically and economically available, the payload fraction for a given maximum depth will increase.

Although a standard definition of what is included in the payload is important to prospective users, operators and users have not yet adopted one. In a recent survey, I proposed the following definitions to a majority of the owners and operators of research submersibles in this country. Since 10 out of 11 respondents agreed that it would be satisfactory, it is proposed here as a standard; the wording being adjusted slightly from that of reference (*8*) for clarification.

$$P = B - Ws,$$

where P is the standard net payload, in pounds (the weight of the payload in water); B is the total buoyant force (pounds) when submerged in water of density 64 pounds per cubic foot at maximum operating depth in diving trim (B does not include any buoyancy of payload); Ws is the weight of hull, machinery, crew, equipment, and systems necessary for safety, operation, and navigation at full depth. All systems including propulsion to be fully charged. Weight of one person plus clothes assumed to be 200 pounds. Thus, P (payload) is the maximum weight of people, material, and anything else which the scientist or user can place aboard to accomplish the mission.

Principal Technical Problems

Aside from wanting better strength-to-weight ratios for hull materials, there are a number of other technical problems for which satisfactory solutions are not now available at an acceptable cost. Chief among these are (i) the limited ratios of energy to weight and energy to volume available in batteries; (ii) the tendency of electrical cables, fittings, and connectors to leak when subject to the pressure cycling of repeated dives; (iii) the difficulty of fixing position accurately or returning to a given precise location when submerged; (iv) the restricted vision of the observer which is limited both by the short range of visibility in water and by the limited number or the location of ports; and (v) the inability of the small submersible to operate in anything but relatively calm seas—largely because of the still unsatisfactory methods of launching and recovery from supporting surface ships.

An additional circumstance, important for the scientist to understand, is the limited percentage of the total time which can be spent at the site

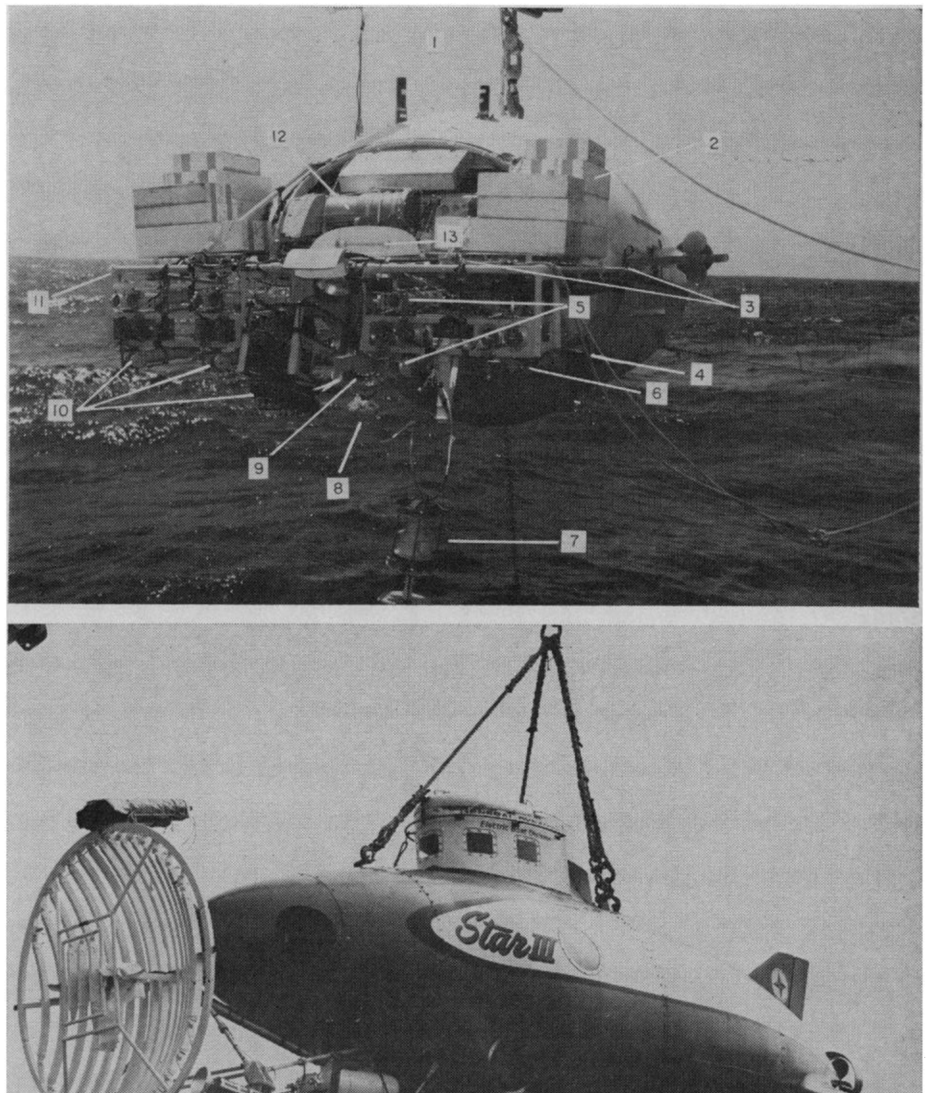

Fig. 3. Examples of submersibles that have accomplished successful missions. (Top) The research submersible *Deep Star 4000* built by Westinghouse and fitted with a "brow" to carry instruments for scientists of the U.S. Naval Electronics Laboratory. (1) Acoustic pingers; (2) flotation blocks; (3) explosive release bolts; (4) mechanical sampling claw; (5) water-sampling bottles; (6) strobe lamp; (7) Savonius rotor-current measurement instrument; (8) dye marker; (9) bottom-temperature probe (retracted); (10) water-sampling bottles; (11) basic equipment mounting framework; (12) forward mercury cylinder; (13) movie lamp. (Bottom) General Dynamics' research submersible *Star III*. During recent missions for the U.S. Navy along the Atlantic Continental Shelf and off Bermuda, *Star III* made 40 dives, 18 of them exceeding 1000 feet (300 m), and logged nearly 100 hours, submerged time. The submersible carried special research equipment, including a 5-foot (1.5-m) parabolic reflector transducer, mounted on its bow, for studying underwater-sound propagation.

of his observation. Two factors are relevant: first, the ratio of the number of days on which dives are made to the total calendar span (charter) and, second, the ratio of the number of hours on the bottom to total number spent under water. One of the newest research submersibles, working on a long-term charter, produced these statistics which may be taken as representative of operations in southern U.S. waters. Out of 187 calendar days, there were 101 operating days (54 percent) (37 days were needed for maintenance and on 49 other days dives were not scheduled owing to weekends, holidays, and so forth). Of the 101 operating days, 13 were lost because of weather, leaving 88 days (47 percent of the calendar span) on which 107 dives were made for the customer. Ninety-nine dives were completely successful and eight were partly successful.

During other, shorter charters, RS have made dives on as many as 70 percent of the chartered days. At Palomares, while under great pressure to find the lost nuclear weapon, *Alvin* made 34 dives on 34 out of 53 calendar days (64 percent). Seven days were lost because of weather. During the 34 dives, *Alvin* spent 228 hours under water, an exceptionally high average of nearly 7 hours per dive. However, it must be remembered that these men were working under unusual incentive and near the limit of their physical and material endurance.

Whether the mission is search or research, time under water is not all productive. In his analysis of the Palomares search operation, Daubin (*9*) introduces the "bottom time fraction," R_b, where R_b is the ratio of the time on the bottom to the time under water. Contemporary research submersibles have not been designed to descend or ascend at large angles and, except for the nearly completed *Dowb*, their rate of vertical travel is less than 200 feet (60 m) per minute. In 35 dives at Palomares, *Alvin* used about 33 hours to cover 163,930 vertical feet (25 miles). For the *Alvin*, R_b was therefore 195/228 or 85 percent. Of course, this "bottom time fraction" depends on the depth of water and the duration of the dive as well as the rate of ascent and descent. Submersibles designed for very great depths will need to maximize this rate.

Time under water may be a relatively small portion of the working day of the submersible. In general each

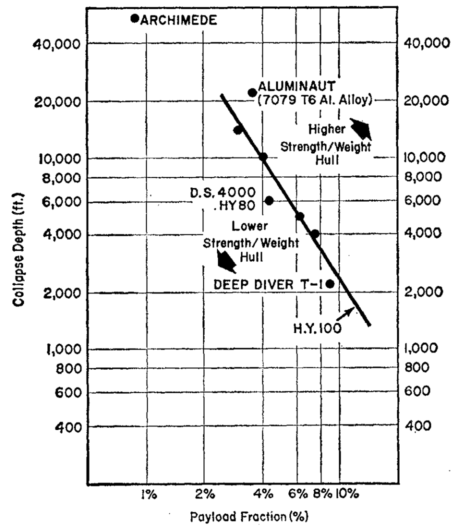

Fig. 4. The line shows the empirical relationship of payload fraction to depth at which pressure hull will collapse, based upon four current submersibles with hulls built from a steel alloy having a yield strength of 100,000 lb/in². Some other submersibles with pressure hulls having higher and lower ratios of strength to weight are shown for comparison. "Collapse Depth" is generally 1½ to 2 times maximum operating depth.

dive includes the following elements: (i) Transit from the anchorage or base to the diving location (if the distance is more than a mile or so, the submersible must be towed or carried on the support vessel), (ii) launching of the research submersible from the support vessel and check-out before diving, (iii) descent, (iv) operations on the bottom or other site of research, (v) ascent, (vi) recovery of the RS from the water by the support ship, (vii) transit to the anchorage or other overnight base, (viii) maintenance work on the submersible, and (ix) rest for the crew, if only one crew.

Daubin (*9*) labels the ratio of time under water to total calendar time the operational duty cycle, R_d. For the *Alvin* operations at Palomares,

$$R_d = \frac{228}{53 \times 24}$$

or 18 percent. Thus, if a scientist can estimate that he will require H hours of observation time on the bottom, the total calendar time required can be estimated as

$$T = \frac{H}{R_d \times R_b}$$

where R_d and R_b are values appropriate to the particular submarine and operation.

Charter versus Ownership

Among the scientists that have used research submersibles there is almost unanimous agreement that these craft should be chartered for research rather than owned by the laboratory. Although it is unquestionably true that a better submersible than any in existence could be built for any given type of work, owning such a craft has its drawbacks for the average laboratory. The diverse and flexible requirements of several researchers are less adequately served than if each can choose and charter the most appropriate submersible. Furthermore, owning a small submersible without also owning a support ship seems to be impractical. Thus, the operations, maintenance, and funding responsibilities, generally burdensome to research-minded people, are extended to a complex system.

Piloting and maintenance skills required to operate the larger, deeper-diving craft, with their increasingly sophisticated instrumentation, are approximately equal to those needed to operate a contemporary airliner. On the other hand, submersibles for most exploration of the continental shelf can be much simpler. Some day, as one scientist suggests, it may be practical for each especially interested investigator to pilot these simple craft like his own car. Under these circumstances ownership by a large institution that has surface ships and other support facilities may become attractive, particularly if the mission of the institution includes some rather standard underwater tasks.

Costs

Except for a few craft with a maximum operating depth of 300 to 600 feet (90 to 180 m) the selling price of those submersibles which can be bought today runs to six or seven figures. Those few manufacturers who have built more than one craft have experimented with different designs so that the quoted prices are not representative of a developed market.

Charter rates vary with depth of operation, with length of charter, and with surface support required. The smaller shallow boat can be rented, without support, for around $1000 per day and the larger boats, with surface support, must charge around $100,000 per month to cover expenses. Insurance is a major element of the annual operating cost, amounting to almost one-third of the total in some cases. When the inspection requirements being developed by the American Bureau of Shipping are widely accepted, the argument for a more reasonable insurance rate will be strengthened.

Principal Accomplishments

Despite the limitations and occasional frustrations associated with this developing tool of research, more than 150 U.S. scientists have made dives since the beginning of 1965 (Fig. 5). It is expected that the final 1967 totals will exceed those of 1966. The same submersibles have also made at least an equal number of dives for purposes other than research during these years.

Not all research dives were successful. Records (*8*) show that about 10 percent were aborted or failed to accomplish their purpose, chiefly because of instrument problems, but occasionally because of ocean conditions or the inability of the submersible to accomplish the mission. In about 50 percent of the remainder, the success of the dive was rated "fair" by the investigator and the other 50 percent were rated "good." Representative examples of scientific accomplishments have been listed under the special features of the submersible which made the work possible, easier, or more effective than if another tool had been used (*10*).

Observation at the Site

Without question the most valued feature of the submersible is that the observer can visit the site and make direct records of his observations. Examples of the work thus made possible are direct, prolonged observation of the behavior of marine organisms and of the fine variability in sediments; observation of sediment transport and features of deeply submerged canyons; observation of near bottom currents with dye; discovery of extensive terraces on the continental shelf; correlation of the biota with the nature of the bottom sediment; proof of the existence of life at the deepest known spot in the ocean; exploration of the bathymetry and biota of Lake Michigan, revealing the existence of a mid-lake sill, glacial boulders, and snowlike precipitation.

Precise Placement of Instrumentation

As a result of bringing the research submersible to the general area, selecting the preferred spot for making the measurements, and then placing the instrumentation within centimeters of where it is desired, new knowledge of the interface between sea and sea bed has been gained. Examples of the areas investigated include: water motion, sound channels, and chemical gradients at the sea floor, and precise heat flow at the interface; shear strength, shear velocities, and sound velocities in the bottom sediment; sound velocity and a new type of pulsing current near the bottom; seismic

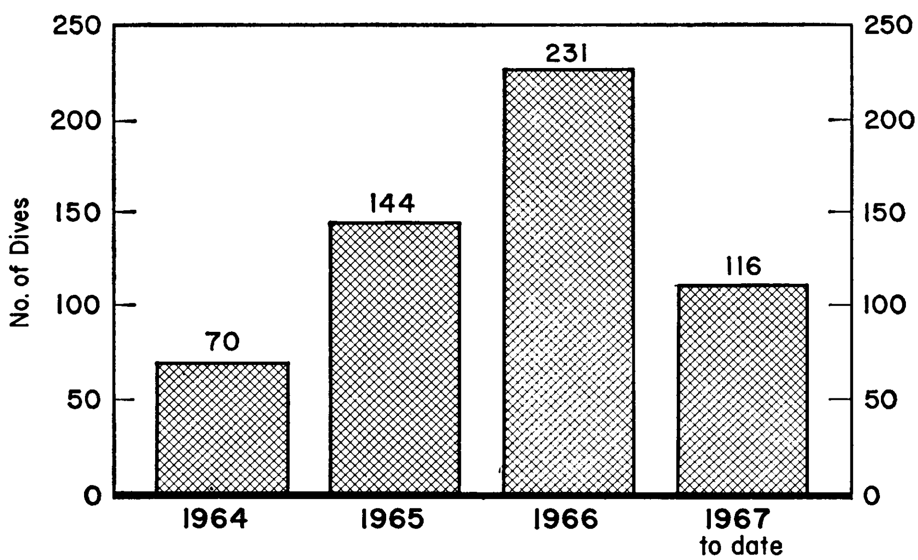

Fig. 5. The approximate number of dives made for research purposes by U.S. scientists to date. A large number of dives made by Scripps and N.E.L. personnel in the Cousteau *Saucer* in 1964 and 1965 are included, but not dives for inspection, indoctrination, recovery operations, or other reasons.

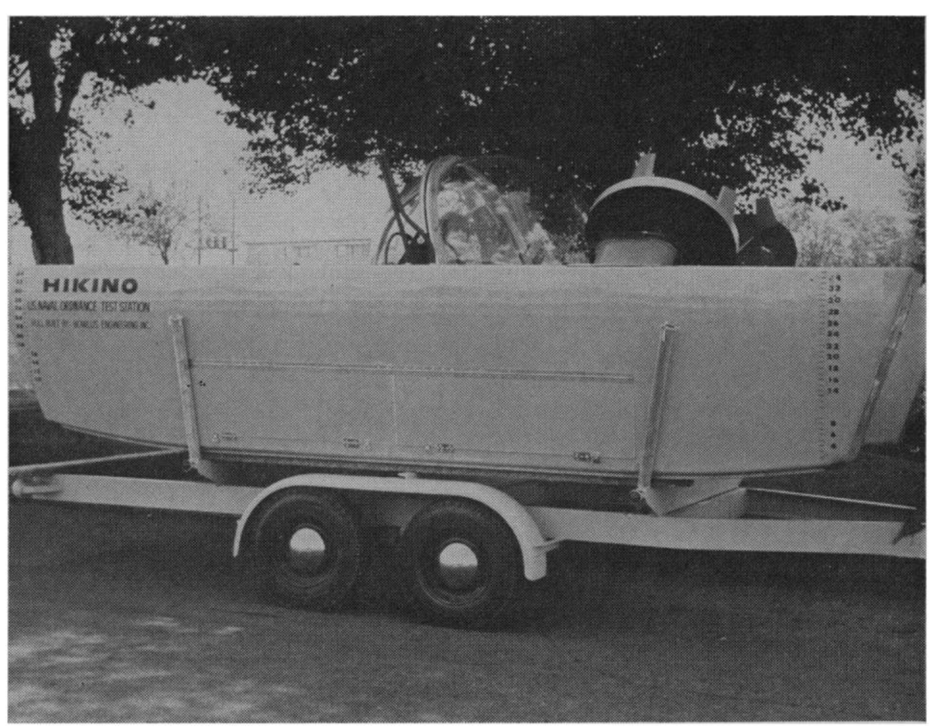

Fig. 6. A "mockup" of the simple and unique submersible with a transparent pressure hull being developed by the Naval Ordnance Test Center at China Lake, California. The tankage, power plant, and equipment are contained in the catamaran-type structures on either side of the personnel "bubble." Propulsion and maneuverability will be provided by cycloidal-type propellers.

background noise; and calibration of wire-lowered acoustic sensors.

Hovering in midwater depth permitted direct observation of the vertical migration of the deep scattering layer, identification of responsible organisms, and correlation with surface sonar performance.

The ability to sit on the bottom and level the axes of the submersible made it possible to measure bottom slope accurately and to make gravity measurements at the sea bed with much greater precision than with remote-control equipment.

The ability to survey, change course or stop, sample, return to the site, and pursue unexpected opportunities enhances the interest and efficiency of the observer. Some of the work made possible by these characteristics are observation of the spatial distribution of fauna; observation at leisure and easy mapping of underwater archeological finds; and the ability to transport divers to various sites in relative comfort, which, when coupled with diver lockout capability, provides an effective mobile diving station.

Payload Capability

The ability to carry a relatively large number of instruments or to recover objects is an important aid to science as well as to search and recovery operations. For example, (i) Kaiser and Assard of the U.S. Naval Underwater Sound Laboratory were able to mount a parabolic reflector, electronic diver, transducer, monitor hydrophone, and associated equipment on *Star III* (Fig. 3, bottom) to make volume reverberation and other acoustic measurements at 2000 feet (600 m). (ii) Schwendinger of the Underwater Sound Laboratory mounted a T-shaped fiberglass boom (24 by 10 feet) to support sensors for measurements of electromagnetic noise at precisely selected spots in depths down to 1200 feet (360 m). (iii) Workers on the *Aluminaut* recovered a single slab of manganese oxide weighing 91 kilograms and, on another dive to 960 meters, retrieved a current-meter array weighing 950 kilograms.

Future Trends

In response to a questionnaire which I mailed (*8*) virtually every scientist who uses a research submersible replied that he expects to continue to expand the use of RS in his work. No less than ten submersibles of this type are under construction in the United States at the present time. One can safely predict that the trend shown in Fig. 1 will persist.

The pace and manner of development of the submersible seems reasonable. With but a single exception, all manufacturers have built only one of each design, a circumstance which has kept costs high but which has allowed a good deal of experimentation.

For the future, two technical development trends can be expected. It will soon be possible to design small, simple-to-operate, standardized submersibles for 600- to 1000-foot (180- to 300-m) maximum depth that will serve many purposes at a lower cost. The principal technical problem remaining arises from the concurrent need for a simple launching and recovery system that can be operated from a small conventional ship. Private industry, in its traditional competitive role, is fully capable and suited to carry out this development independently.

The second trend will concern itself with extending the technology to find solutions to the difficult problems of greater speed, depth, endurance, high visibility, operability in rough seas, and improved equipment. Perhaps this can be accomplished best, as suggested in the summary of the Woods Hole Workshop Conference (*11*), by building a number of prototypes each emphasizing one or two of these characteristics before attempting to close in on an optimum design. A number of materials with higher strength-to-weight ratios—metals, nonmetals, and composites—are becoming available. On the power side, fuel cells offer more power and endurance for the weight and space available than batteries and nuclear plants (reactor or isotope) and hold promise for very long endurance dives. The technology for major improvements in these important characteristics is at hand but some of the development programs for small submersibles will be costly. It is likely that they will have to be supported in a major way by government funds. The Navy's Deep Submergence System Program is already funding much of this development, including a 2000-foot (600-m) submersible (*DSSV*) and a nuclear reactor powered submersible that will be able to remain submerged for 30 days (*NR-1*). Both of these vehicles will be complex and costly and it is not likely that they will be used extensively for general scientific research. The newly formed National Council for Marine Resources and Engineering Development has emphasized the need for a strong program of deep ocean technology and looks to the Navy as a principal agent (*12*). Much of the technology developed by these programs will be available to improve general research submersibles.

Tenders and Support Ships

The search for a satisfactory support base with launching and recovery equipment to allow work in sea states greater than 3 to 4 must continue. No doubt in the next few years there will be experiments to launch and recover research submersibles from *Flip*-type ships and perhaps from locks or hatch-covered entries to caverns under the sea bed. In addition, as suggested (*11*), submersibles should be developed to be compatible also with surface and submerged laboratory ships, tethered vehicles, and other submerged devices.

Visibility

Lack of adequate viewports is the most outstanding weakness of first-generation research submersibles. Research and development such as that of Perry at the Naval Ordnance Laboratory and McLean at the Naval Ordnance Test Station will produce a nearly perfect solution—a strong yet transparent glass hull—before long. Figure 6 shows one version.

Reliability

Unquestionably one of the most critical needs of submersible technology today is to obtain reliability of components and circuitry. Corrosion, electrolytic action, high humidity, high stress, and the pressure cycling, which results from repeated dive and other adverse factors, combine to make this a much more perplexing and difficult problem than most scientists or engineers realize. Submersibles can be kept on a reasonable operating schedule only by virtue of daily maintenance. During the search for the *Thresher*, it was nearly impossible to keep *Trieste II* in operation without a long trip back to drydock. As part of the development program for the nuclear submersible, *NR-1*, the Navy is making a major effort to improve the reliability of components so that the prolonged power endurance of the nuclear reactor can be utilized.

Summary

The past decade has seen the development of small submersibles as a new and effective tool of geology, acoustics, marine biology, and physical oceanography. As with all tools, it has special capabilities and limitations. The methods of use and the needed engineering improvements are being identified. Scientists, engineers, government, and industry are responding so that advances toward both less-expensive simple vehicles and high-performance complex vehicles are proceeding.

The National Council for Marine Resources and Engineering Development has stated, "By a number of circumstances, some of the result of planned marine development, but the most fortuitous contributions from other fields, we find the technologies ripe for meeting new marine requirements" (*12*). Apart from technologic advances there is (i) a continuing need to make scientists in many fields aware of the capabilities and possibilities of research submersibles. This can be done most convincingly by taking prospective investigators on a dive; however, there are but few seats, and dives cost more money than some owners feel they can afford on a continuing basis. It may thus be necessary to catalyze this process with some limited-term government support. There is also (ii) a need for intelligent construction standards and safeguards, both to enhance safety and provide a basis for reasonable insurance rates. Regulation of construction and operation is necessary for public good, but it should be kept to a minimum in order not to stifle development of an infant technology.

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NEWS AND COMMENT

Euratom: After 10 Years, Still Seeking the Way

Brussels. For some time the news of Euratom, the atomic energy organization of Europe's "Six," has been gloomy. Budget difficulties, uncertainties about internal structure, and, most important, questions about the agency's mission have led many to take a pessimistic view of Euratom's future. However troubled the present, Euratom's functions are nevertheless too valuable to be written off, although its form may alter considerably from that envisioned when the organization was established a decade ago.

One of Euratom's most pressing problems was dealt with in July when agreement was finally reached on its budget for the present year. Since 1967 is the last year of Euratom's second 5-year program, one of the results of the budget impasse was to block development of a third 5-year program. Consequently no new research program for next year has been accepted.

The basis for the July agreement was the settling of two disputes that have plagued Euratom. In the first case, a compromise was reached under which an Italian fast-reactor research program was given limited-term support by Euratom. In the other, the French Government agreed to advance $2.8 million for plutonium supplied by the United States for a French reactor at Cadrache. The cost was incurred when the U.S. Government decided to sell rather than lease the plutonium; the French argued that the responsibility for paying for it was Euratom's.

Coinciding with the budget crisis was a reorganization of the administrative structure of Euratom and, in fact, of the Brussels "Eurocracy" of the Common Market countries (Belgium, France, Germany, Holland, Italy, Luxembourg). What this amounts to is abolition of separate commissions and their replacement with a merged 14-man commission to head the Common Market, Euratom, and the European Coal and Steel Community.

In the case of Euratom a form of administration is supplanted which often seemed to magnify the political and