Aluminaut

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The Aluminaut, a deep submergence, oceanographic research submarine, is now undergoing builder's sea trials offshore from Groton, Conn. Built for Reynolds International, Inc., the Aluminaut called for development of a pressure hull with an acceptable strength-to-weight ratio for operation at a design depth of 15,000 ft. Penetrations for the electrical power and instrumentation leads and access and viewing ports were carefully analyzed. Weight was meticulously monitored so that an effective scientific payload of 3400 lb could be maintained. The vessel was hydrodynamically faired on the exterior to maintain a maximum speed of 3.8 knots and a specified range of 80 naut miles. The design also entailed provisions for 32 hr of submerged operation for a crew of three under normal conditions, with emergency provisions for extending this period to 72 hr. Possible research uses and commercial applications are briefly discussed.

Introduction

THE "Aluminaut" project was a result of the recognition by J. L. Reynolds and W. G. Reynolds of Reynolds Metals Company (RMC) of the need for a deep submergence vessel that could cruise at great depths for protracted periods of time. The first step in this project was a feasibility study to determine in broad terms whether an oceanographic vehicle could be designed to operate at depths up to 15,000 ft, carry an acceptable payload of scientific equipment and personnel, and have the speed, range, and maneuverability to be effective as a deep ocean exploration vessel. This study was conducted for RMC by Southwest Research Institute (SRI) in San Antonio, Texas. under the direction of E. Wenk. The finding of this study[1,2] was that a ship of such characteristics could be designed and built using materials and components that were within the "state of the art."

Design Considerations

For the purposes intended, it was determined that a stiffened cylinder was the most efficient shape for the pressure hull. The weight-vs-buoyancy characteristics of stiffened cylindrical hulls of different materials are shown in Fig. 1. Hulls with excess buoyancy will float, and the amount of buoyancy is a measure of deadweight and payload.[3] Deadweight in this case is made up of structure, propulsion motors and batteries, crew, and internal fixtures including the complete life support system. In addition to a high strength-to-weight ratio, the material chosen had to have desirable manufacturing characteristics within the current state of the art. On the basis of these criteria, aluminum alloy 7079-*T*6 was chosen having an equivalent yield strength of 60,000 psi in the thicknesses required, the yield strength being based on 0.2% of the stress-strain curve. At a depth of 23,000 ft, the excess buoyancy of this alloy is 31%, a figure adequate to compensate for deadweight and payload.

Hull Design

The major design problem was the integrity of the pressure hull. Because the material chosen for the hull is difficult to weld using standard arc-welding techniques, particularly in the size of sections required, the hull sections were designed to be held together by mechanical means. Figure 2 shows a schematic view of the hull cylinders and hemispherical heads with their associated main stresses. There are a total of eleven hull cylinders, each one having a 97-in. o.d. and 84-in. i.d. The internal flange is $1\frac{1}{2}$ in. wide by 5 in. deep. The hull is $6\frac{1}{2}$ in. thick. Notice that the hoop stresses in the cylinder are greater than those in the head. The head, therefore, is the only area where penetrations, such as windows and hatches, are located. Figure 3 shows that the maximum stresses in a single axis in compression at 15,000 ft are slightly greater than 50,000 psi. The areas of maximum stress are all areas where multiaxis stress conditions exist. To determine both the stresses and the collapse pressures, the analysis was substantiated with a program of model tests[4] at SRI. The experimental results agreed very well with the theoretical predictions and thus confirmed the validity of the assumptions made.

Hydrodynamics and Stability

The resistance, stability, and towing characteristics of this vessel were extremely important; consequently, a $\frac{1}{16}$ scale model of the proposed design was made and tested in the rotating arm tank at Stevens Institute of Technology (SIT). Initial tests showed discontinuities in both the lateral force and yaw moment curves. Since the discontinuities appeared at yaw angles near 2°, corrective measures were made before proceeding further with the tests. It was concluded that the discontinuities in these stability curves were caused by the large thickness-to-chord ratio of the after access trunk

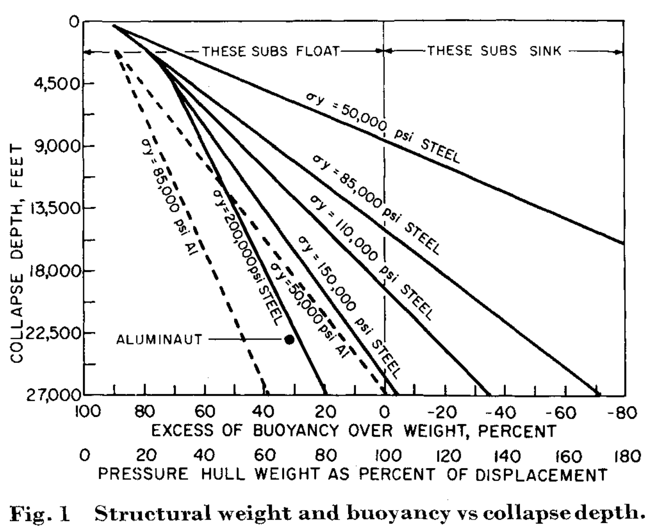

Fig. 1 Structural weight and buoyancy vs collapse depth.

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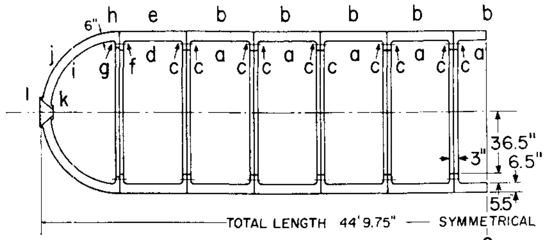

LOCATION	LONGITUDINAL STRESS	CIRCUMFERENTIAL STRESS	VON-MISES YIELD CRITERION STRESS
a	24	50	43
b	30	46	34
c	30x(1.4)+= 42	51	47
d	19	49	43
e	34	47	35
f	22x(1.4)+=31	41	37
g	37x(1.43)+=53	41	48
h	22	32	22
i	34	33	34
j	29	29	22
k	2	46	45
l	2	54	50

( )+ EXPERIMENTAL STRESS CONCENTRATION FACTORS

Fig. 2 Aluminaut pressure hull.

which was causing flow separation and consequently stalling at this fin. On bare hull tests these discontinuities disappeared.

Flow visualization tests were made at the General Dynamics/Electric Boat (GD/EB) smoke-wind tunnel. Tufts were used at selected locations and manual pressure readings taken. On the original model, steady unseparated flow, incipient separation, intermittent separation, and fully separated flow were identified. Small separated flow regions were observed on the top of the forward access trunk, on top of the after trunk, on the aft portion of the keel, and on the rear of the vertical propeller nacelle, and a large region of separated flow was observed on the sides of the after access trunk. By minor modification of the designs and on the model itself by use of plasticene, a synthetic clay-like material, the areas of flow separation were eliminated or greatly decreased. The model was then retested in the rotating arm tank at Stevens, and the results proved successful. Figure 4 is a picture of the model used for tests. Figure 5 shows horsepower vs speed and resistance vs speed, and Fig. 6 shows moment coefficient vs yaw angle.

Selection of 7079 Alloy

Two factors that governed the selection of 7079 alloy for the hull structure are strength level and section size. Only 7079 had the necessary strength in the large sections and in the thickness required. Design considerations required 60,000-psi equivalent yield strength in sections $6\frac{1}{2}$ in. thick. Other alloys (7075 and 7178) have slightly superior properties in

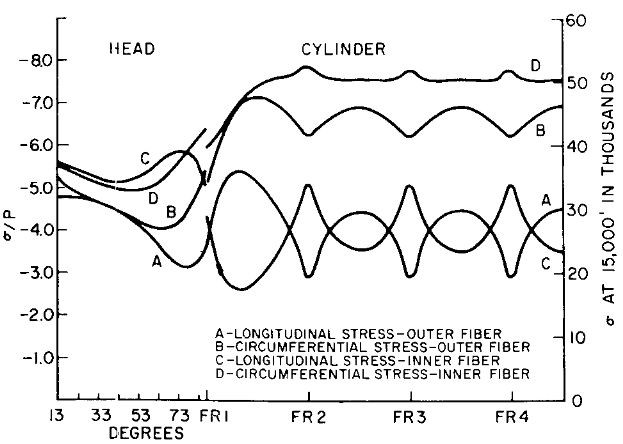

Fig. 3 Detailed stress analysis of hull.

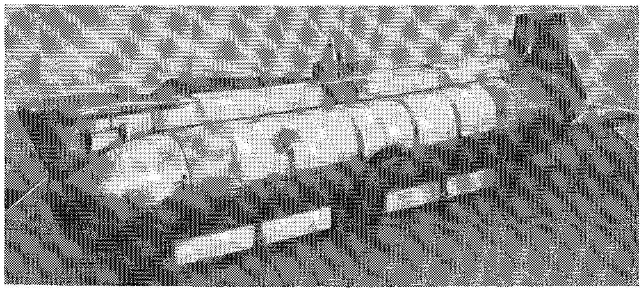

Fig. 4 Test model.

thinner sections but have additional complexity in heat treatment in large sections.

It was recognized that 7079 has some limitations from the standpoint of fatigue and corrosion. However, all of the steel-and-aluminum alloys deteriorate in their physical characteristics when used in such thicknesses as those required, as shown, for example, by the rotating beam fatigue strength data in Fig. 7. In addition, all such alloys need protection against corrosion. Under these circumstances, considering all requirements, 7079 was the best alloy. A more corrosion-resistant material would have much lower strength and, therefore, require a thicker hull.

Stress Corrosion

Stress corrosion cracking occurs as a result of an interaction of sustained tensile stress and corrosive attack, which results in brittle-type failures in an otherwise ductile material. The surface direction of the cracks is perpendicular to the direction of applied stress. Stress corrosion cracking does not occur in material in compressive stress. The important points therefore are 1) a sustained tensile stress and 2) environmental conditions to cause corrosive attack. Normally intermittent surface loads on structures do not cause stress corrosion cracking to take place. For most materials and environments, there is a threshold stress level below which stress corrosion cracking will not take place. This

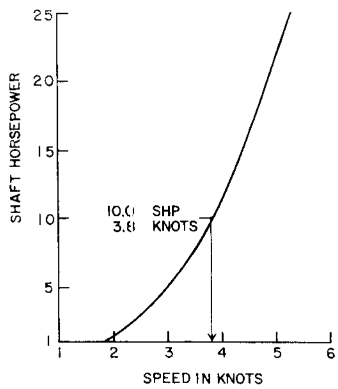

Fig. 5a Aluminaut submerged, speed vs shaft horsepower.

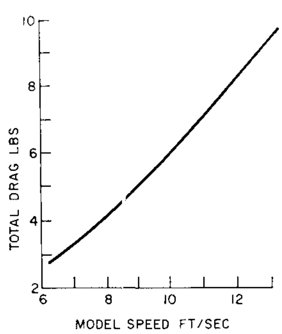

Fig. 5b Total drag submerged, Aluminaut model 5.

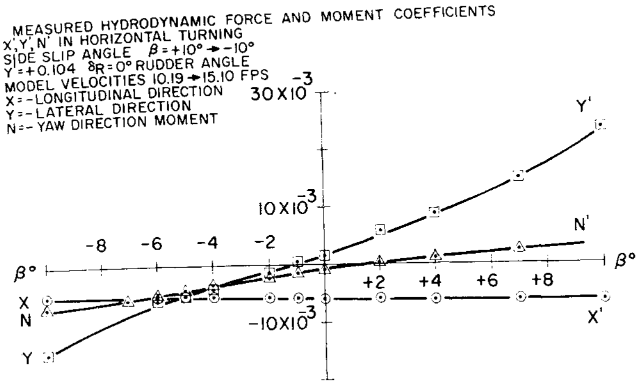

Fig. 6 Submerged test, Aluminaut Model 5; centerline 2 ft below surface.

threshold stress level is independent of time and temperature. In 7079 alloys, resistance to stress corrosion cracking is also a function of the direction of applied stress relative to direction of forging flow. The threshold stress level is higher for stresses applied perpendicular to forging flow. Sprowls and Brown[5] have presented some data showing the following threshold tension stress levels as a function of forging direction for immersion of 7079 forgings in sodium chloride solutions and in sea-coast atmospheres: longitudinal, 50,000 psi; long transverse, 30,000 psi; and short transverse, 7000 psi. These values are for a particular test only on forged bar specimens and do not necessarily hold true for other forgings. The forging shape, amount of work in each direction, and forging thickness will influence the threshold stress, but these values show relative orders of magnitude.

A thorough stress corrosion analysis has been made for the Aluminaut, particularly relative to tensile stress level and corrosion protection. The structure essentially will be subjected to compressive loads only. One area of concern is the many holes to be drilled on the outside of the hull to attach the superstructure. The drilling of these holes will expose the end grain in the short transverse direction (perpendicular to forging flow). This problem has been resolved by completely filling the hole, that is, using an interference fit pin in this hole and also by thoroughly capping the pin to provide sealing to prevent the entrance of water. In addition, all of the aluminum portions of the Aluminaut will be treated with a deoxidine-alodine treatment and will receive four coats of specialized plastic protection. Each coat will be of a different color so that in case of damage it is known exactly what remedial action is required.

Table 1 gives the properties of various aluminum alloys. The original design concepts included a hull constructed of rolled plate sections. However, as mentioned earlier, the 7079 alloy is difficult to weld using standard techniques.

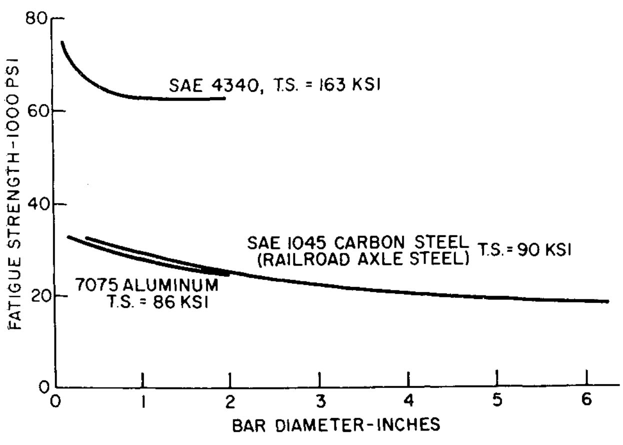

Fig. 7 Material strength deterioration.

Considering the areas of maximum stress, it was deemed undesirable to form the cylinders from plating. Consequently, the final design used flanged ring forgings held together with mechanical connections. Various forging shops were consulted to determine whether means existed to forge seamless rings in the sizes and shapes necessary. We found the size was within the capabilities of several shops, but that no one had ever forged such a large piece of aluminum; nor had ingots of the size required ever been cast. Reynolds Metals Company agreed to produce the large ingots, and Ladish Company undertook the development to forge the cylinders. The production of the ingots required considerable study and developmental effort. After a redesign of its ingot molds and pouring facilities, the McCook plant of RMC was able to produce ingots weighing as much as 35,000 lb.

The ingots used to produce rings or cylinders were approximately 24 × 72 × 99 in. and weighed slightly more than 17,000 lb. For the heads or domes, ingots were slightly smaller, about 14,000 lb. All ingots were ultrasonically inspected for defects before any forging was started. Those not meeting standards were rejected.

To produce the cylinders, the large rectangular ingots were heated and forged under large hydraulic presses. Initial operations changed the shape to a cylindrical shape that was upset or pancaked. The center was then punched out. By mandrel forging on a large press the cylindrical shape began to become apparent, growing larger in diameter and thinner in wall. At many stages of forging, the material had to be returned to the furnace and reheated. With the selected material, the high strength of the material made forging difficult. Following the forging on the mandrel, the partially shaped piece was transferred to a large ring-rolling machine and rolled to the final contour. The forged cylinders after ring rolling weighed 14,000 lb. A rough machining operation removed excess metal prior to heat treatment. Heat treatment consisted of heating to 830°F for 48 hr.

The procedure for making the heads was slightly different. The rectangular ingots were forged to a round shape and upset to a squat cylinder. The upset forgings were then further shaped by a series of forging operations in large forging equipment to a large cup-shaped or hemispherical forging ready for machining and heat treatment. A problem that arose during heat treatment was how to get a rapid quench. If the dome were quenched open end up, it might float on the surface and not get a fast enough cool. If quenched open

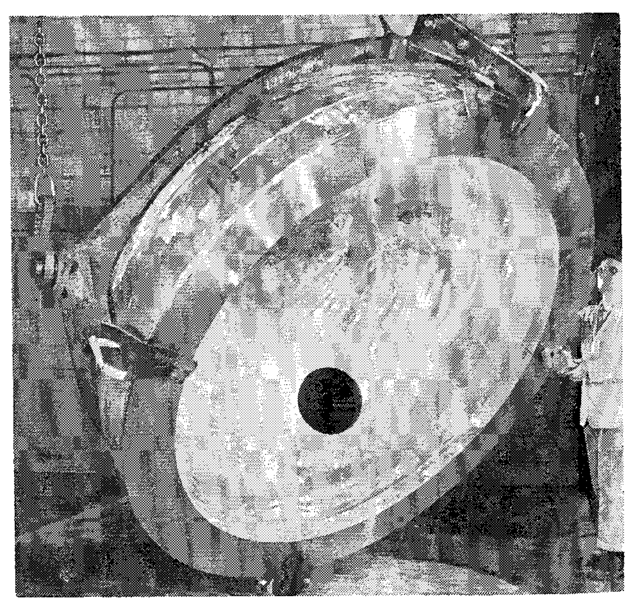

Fig. 8 Head ready for heat treatment.

end down, steam would be trapped inside, again retarding the cooling rate. The final solution was to cut a hole through the head in the location of the hatch. This permitted steam to escape, and a special fixture that was used to pick up the forging also permitted it to be quenched at an angle. Figure 8 shows the head in the condition ready for heat treatment.

Throughout the forging operations problems arose. Aluminum forgings of these sizes had never been attempted before. Special tooling was required, and this had to be modified as more was learned about handling these large pieces. Heating rates and soaking times prior to forging were critical. In order to determine the quality of the material, the first forging produced was sectioned, and tests were made from all of the areas. The results showed where deficiencies existed, and forging procedures were altered to correct these. Finished forgings were also ultrasonically inspected for defects.

Over-all Design

Figure 9 is a phantom view of the Aluminaut showing its interior arrangement. The main pressure hull consists of 11 cylinders and two hemispherical heads as shown. Internally, starting from the bow, the forward hemihead encloses the scientific observer area. There are four observation ports in this hemihead, each approximately 7 in. thick. Aft of this area, the first two bays are for scientific instruments; the next three bays are for batteries and the battery cases as shown. The next two bays are the pilot's station. He controls the vessel from here. In front of him are the ship's control panel and ballast control panel. The next two bays are for more batteries, and the sternmost two bays are for auxiliary equipment. The trim system is internal and allows the pilot to move water fore and aft.

The third man, located aft, not only serves as a scientific observer but controls the vessel while it is on the surface from the aft rudder. The forward observer, from his position in the forward hemihead, can steer the ship, including low-speed control of the motors.

The keel, made of aluminum plate, contains lead for stability and also encloses the high-pressure main ballast tank air bottles that are filled from connections in the sail and feed the 4500-psi air system. On the sides are the main ballast tanks, one on each side forward and one on each side aft. In the center of these tanks, port and starboard, are the shot tanks. These contain a programed amount of shot that is held in the tanks by an electrically magnetized tube. When it is desired to release shot in part or in full, the power is removed accordingly from this tube, and the shot is released.

On top is the superstructure. It is sheet aluminum and affords a walking space as well as an enclosure for wiring and piping and protection for the forward access hatch. In the center is the vertical ascent or descent propeller driven by a 5-hp motor. Aft is the stern structure with two propellers, each driven by a 5-hp motor. The stern structure is one piece and contains the rudder, planes, and their controls. Note that there are no mechanical penetrations through the hull, only electrical penetrations that are pressure proof. The principal dimensions are: length over-all, 51.25 ft; extreme beam, 15.33 ft; draft, normal trim, 8.67 ft; pressure-hull length, 43.33 ft; pressure-hull o.d., 8.08 ft; pressure-hull thickness, 6.50 in.; submerged displacement, 80.9 tons; surface displacement, 73.1 tons; and variable ballast: water, 11,000 lb; shot, 4700 lb; and drop bar, 4400 lb.

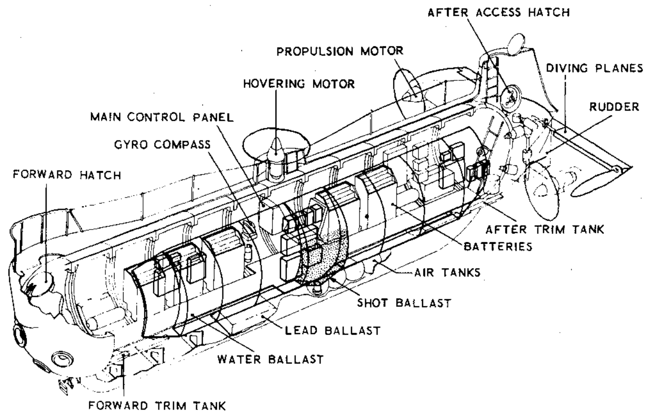

Fig. 9 Aluminaut, phantom view.

Table 1 Mechanical properties for die forgings of aluminum alloys

Alloy	Maximum section thickness, in.	Tensile strength, psi, min	Yield strength 0.2% offset, psi, min	Elongation in 4D, %, min
2014-T6	4	65,000	55,000	7
2018-T61	4	55,000	40,000	7
2025-T6	4	55,000	33,000	11
2218-T61	4	55,000	40,000	7
4032-T6	4	52,000	42,000	3
6061-T6	4	38,000	35,000	7
6151-T6	4	44,000	37,000	10
7075-T6	3	75,000	65,000	7
7076-T61	4	70,000	60,000	...
7079-T6	6	74,000	64,000	7

Operation

From a mother ship or tender, the batteries are charged, the air flasks charged, and all of the scientific equipment, food, and personnel are loaded aboard. A programed amount of shot is then fed into the shot tanks, the amount determined according to the depth required by the mission. At this point the vessel has only 1.5 ft of freeboard (for a 10,000-ft mission).

To submerge, the ballast tanks are vented, giving the vessel negative buoyancy. The vessel will then descend to the programed depth. Descent can be aided by putting a down angle on the stern planes and driving the vessel down by its propellers. At the programed depth, the vessel will reach a point of equilibrium. Ascent or further descent, up to approximately 500 ft, can be obtained by driving the vessel up or down with the vertical propeller. In addition, vertical ascent can be controlled by dropping small amounts of shot from the shot tanks, allowing the vessel to rise to a new depth where it will regain its neutral buoyancy.

When the mission is complete, the shot solenoid is de-energized, the shot is dropped, and the vessel now has positive buoyancy and will start to rise. Again power can be used. At or near the surface, the ballast tanks can be blown to obtain maximum freeboard. In case of emergency at deep depths, a 4400-lb emergency droppable lead weight can be jettisoned for rapid ascent. The major design characteristics are: design depth, 15,000 ft; design speed, 3.8 knots; design range, 80 naut miles; endurance, 32 hr with emergency provisions for life support for 72 hr; crew, 3; and scientific payload, 3400 lb.

Uses

The oceans cover approximately three-quarters of the earth's surface, and over 60% of this high ocean mass lies within the Aluminaut's 15,000-ft design depth. The Aluminaut can be of considerable value for oceanographic exploration and research in the following three broad categories.

Basic Oceanographic Research

This category will include the following measurements: temperature, pressure, current patterns, gravitation forces, magnetic characteristics, salinity, and radioactive background.

Basic Geological Research

This category deals with the study and description of the ocean floor and includes the following: investigation of surface features, bottom coring, sediment sample, seismic measurements, location of mineral deposits, and placement of devices for mining, dredging, or drilling.

General Exploration and Experimentation

This category includes commercial applications as well as scientific studies and covers, for example: surveying construction repair or recovery of bottom-mounted hydrophone arrays; surveying construction and repair of cabling; salvage and recovery of equipment; experimentation with sound propagation at various depths; precise placement of bottom-mounted navigational position-indicating devices; and laying of submerged pipe lines.

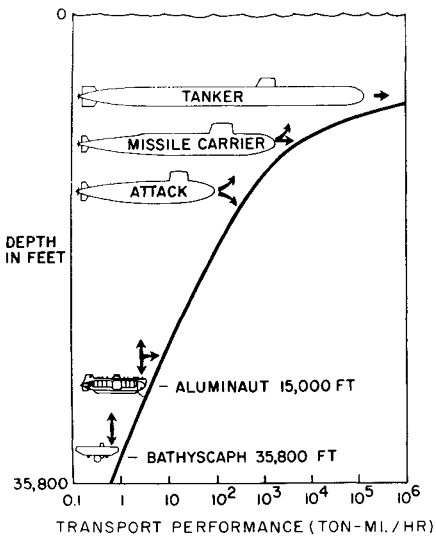

Fig. 10a Transport performance as a function of depth.

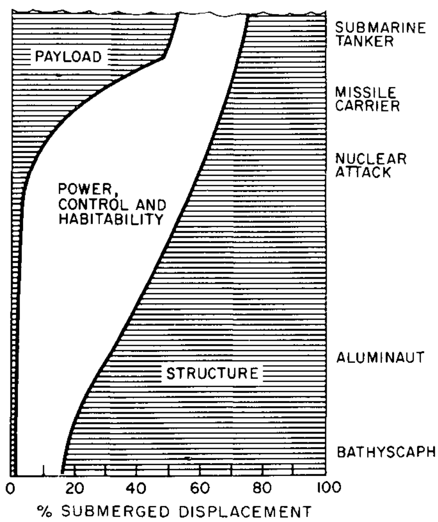

Fig. 10b Weight distribution as a function of submerged displacement.

Figure 10a is a log-log plot of depth vs transport performance (ton-miles/hr) for three classes of submarine. The most obvious application is the transport or tanker, which, in order to be successful, requires large payloads. This operational goal suggests the selection of a path not too far from the interface allowing for low structural weight requirements. The military systems compromise pure transport performance to gain superior positions in depth and speed as compared to the transport system. On the other hand, the scientific and oceanographic research submarine must go far below the interface. Scientific systems work in advance of transport and military systems and presently use modest payloads and speeds to reach the extreme depth for exploration. The Aluminaut covers a range of performance presently not available by any other vehicle. It is able to move in a horizontal as well as vertical plane, and the vessel will be able to use its 3.8-knot speed to great advantage in overcoming the effects of ocean currents which would prevent the use of other forms of research vehicles. The capacity of its life-support system will add valuable hours of on-station operating time and offers the possibility of further increasing the vessel's versatility through trade-offs between additional passengers, payload, and power sources.

Figure 10b shows depth vs typical weight distribution in percent of submergent displacement for the same classes; again, the most obvious application is the transport submarine, which allows low structural weight fractions. On the other hand, operating at a great depth requires a substantial part of the total weight to be put into the structure of the vehicle. Therefore, scientific vehicles of significant depth capabilities require careful weight analysis and skillful design to minimize a reduction in scientific payload. Military submarines are between the two previously mentioned commercial and military vehicles. Although the structural weight of a submarine is essentially fixed, there can be a trade-off between the weight allowed for power, control, and habitability vs payload and speed. The payload can be divided between freight and personnel.

By changing the sets of batteries for the Aluminaut, large changes are possible in payload and personnel carried, from 22 people (total, no payload) to 7000 lb with a crew of three. The design goals, previously mentioned, require four sets of batteries (Fig. 11). However, if speed and range are more important than payload, the number of sets of batteries can be increased correspondingly, resulting in lesser payload.

The effect of such changes is shown in Fig. 12. By selecting the proper number of sets of batteries and electing the right speed, a substantial variation in operating range is possible between the maximum and the design goal of 80 naut miles, requiring four sets of batteries as indicated. On the other hand, it must be realized that hovering itself

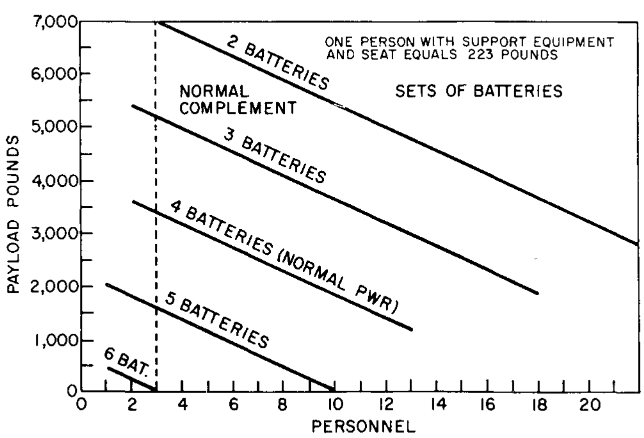

Fig. 11 Carrying capacity in terms of payload, personnel, and batteries.

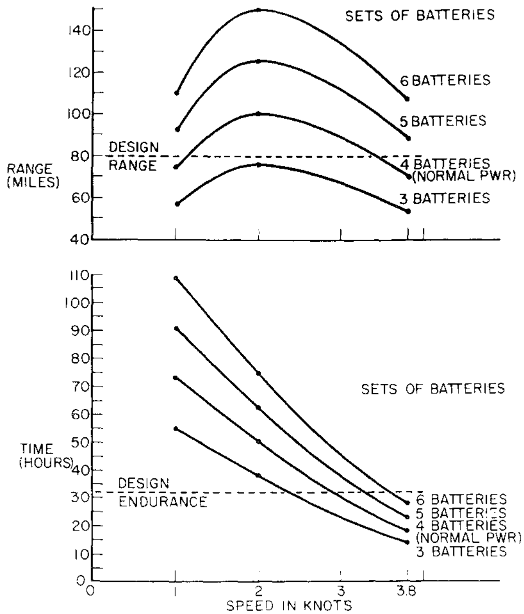

Fig. 12 Endurance, speed, and range performance as affected by battery capacity.

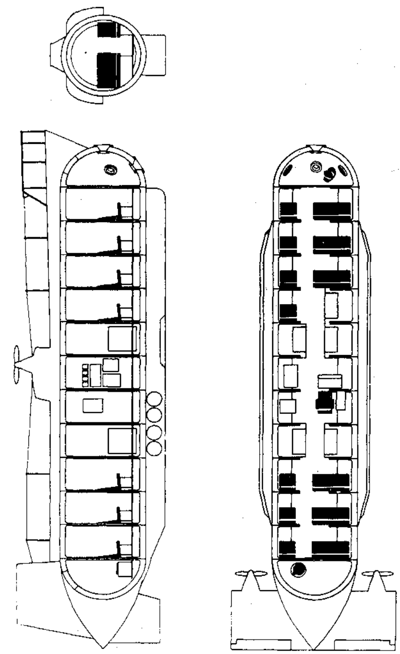

Fig. 13 Potential seating arrangement, 22 people.

requires a hotel load, which is a continuous drain on the batteries, and therefore will affect the operating range if substantial time is spent in hovering. Very low-speed operation has the same effect as hovering, and therefore, for the purpose of this analysis, speeds below one knot are not considered. The desired endurance goal of 32 hr can be more than tripled by selecting the proper speed and sets of batteries. For normal power (four sets of batteries), a wide variance of endurance is possible as a function of speed.

Figure 13 shows an arrangement indicating schematically the seating for a total of 22 people. The 43-ft total length of the pressure hull with an internal diameter of 84 in. easily permits such an arrangement.

The preceding analysis has been made on the basis of using only the two horizontal propellers for forward propulsion. There is a possibility of using the vertical propeller, like a helicopter, as well as of using the effects of buoyancy or displacement force, positive or negative, to influence both speed and range. Such concepts, which could further increase performance, have not been considered in the presented data. The range of possible performance indicates the adaptability and flexibility of which the Aluminaut is capable in meeting a great variety of operating conditions.

In summary, the Aluminaut is a true submarine built to extend the peaceful uses of such craft in the exploration and exploitation of the rich, untapped resources of the sea. As such, it is a significant first step toward realizing the scientific and, perhaps, commercial potential of submarines.

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