Design Considerations of Manned Ambient-Pressure Habitats

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A manned ambient-pressure habitat (MAPH) is an undersea habitat wherein the inhabitants live in a pressurized atmosphere that is contiguous with the sea. In this category belong the U.S. Navy's SEALAB I, II, and III, and Captain Jacques Yves Cousteau's undersea houses. The design of an MAPH presents many novel and challenging engineering problems. SEALAB II was the first design that recognized the MAPH as a true submersible, and therefore followed submarine naval architectural principles. SEALAB III is an enlarged and greatly improved design that increased the operating depth from 250 to 650 ft. This paper discusses these design problems, provides design precautions, and outlines some parameters that require further research, development, test, and evaluation.

Introduction

ON October 10, 1965, the last aquanaut of team 3 secured the access hatch on SEALAB II,† 205 ft below the surface of the Pacific Ocean, and bade a fond farewell to the "Manned Ambient-Pressure Habitat" that had been home to 28 U.S. Navy aquanauts during the previous 45 days. The following day, her ballast tanks were blown, and SEALAB II surfaced, to be towed back to her builders for conversion to SEALAB III. Seven months earlier, SEALAB II did not even exist on paper. How was she conceived, designed, built, delivered, outfitted, tested, and able to complete her experimental mission, all within a time frame of only seven months? This achievement was possible only through the close cooperation and intensive dedication and effort put forth by the many government and private activities involved in the project.

Within the San Francisco Bay Naval Shipyard, which had responsibility for concept, design, and construction of the habitat, SEALAB II's destiny was held within the hands of a small team representing engineering, planning, and production. Design, procurement, and construction were carried out in simultaneous actions, which culminated in delivery of the craft on June 29, 1965, four months from the date of assignment of the task. Yet, for the shipyard, SEALAB II was but considered a small task sandwiched among other big assignments involving naval ship construction, conversion, and repairs.

In the following pages, we will highlight some of the major design problems that were anticipated or encountered and explain how they were solved. For it was only through thoroughness in design that this craft overcame many of the problems experienced in previous manned ambient-pressure habitats (MAPH's).

Basic Specifications

The design of SEALAB II was a real challenge. Hardly any design specifications were given, aside from the requirement to "make the habitat 12 feet in diameter by 50 feet long, and paint it white."

The first problem attacked was one of basic configuration of the hull. Previous MAPH's, e.g., the U.S. Navy's SEALAB I and Cousteau's undersea habitats of Continental Shelf Station no. 2, were emplaced with great sweat and toil. Steel or lead ballast had to be added at the test site through trial and error methods, to sink and emplace these habitats on the bottom of the ocean. Practically all these habitats experienced operational casualties of varying degrees, including flooding.

SEALAB II's naval architects quickly concluded that the MAPH must be designed along the principles of a submarine in which the craft is fitted with carefully sized ballast tanks to give her the required operational flexibility. In addition, she must be designed with positive metacentric height in all modes of operation, to assure stability while on the surface and underwater. Moreover, weight and moment control of the craft, from design through construction, was important to assure that her displacement and other naval architectural design characteristics would be preserved and ultimately achieved.

Configuration of SEALAB II

Figures 1 and 2 show the principal external and internal features and general arrangement of SEALAB II. The main habitat was a pressure cylinder 12 ft in diameter and $57\frac{1}{2}$ ft in length. Four ballast tanks were located on the overhead. Concrete ballast, 21 in. thick, served the quadruple purpose of fixed ballast, a deck, an effective radiant heating system (consisting of imbedded electrical heating cables), and insulation.

High-pressure air could not be used as an atmosphere in SEALAB II since high concentration of nitrogen and oxygen is toxic to the human body. Instead, a 105-psia artificial atmosphere was formulated of approximately 85% helium, 11% nitrogen, and 4% oxygen.

On the surface, SEALAB II had a 20-in. freeboard; access was provided by hatches no. 1 and no. 2 installed in the "conning tower." These hatches were secured prior to lowering SEALAB to the sea bottom test site, at which time the conning tower was used as a ballast tank. Prior to its dive, SEALAB was precharged to about 110 psia. At the sea floor, the gas pressure inside SEALAB was equalized with the sea pressure, so that main hatch no. 3 could be opened and kept open. Gas pressure kept the sea out and maintained the water level at the bottom of the water trap as shown. Aquanauts could then come in and out of SEALAB at will via this access. The water trap consisted of a watertight steel skirt around the hatch. SEALAB II was imbedded firmly to the sea floor by four pointed spades mounted on the four legs of the craft.

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† "SEALAB II" refers to the submersible habitat; "Project SEALAB II" refers to the experimental project as a whole.

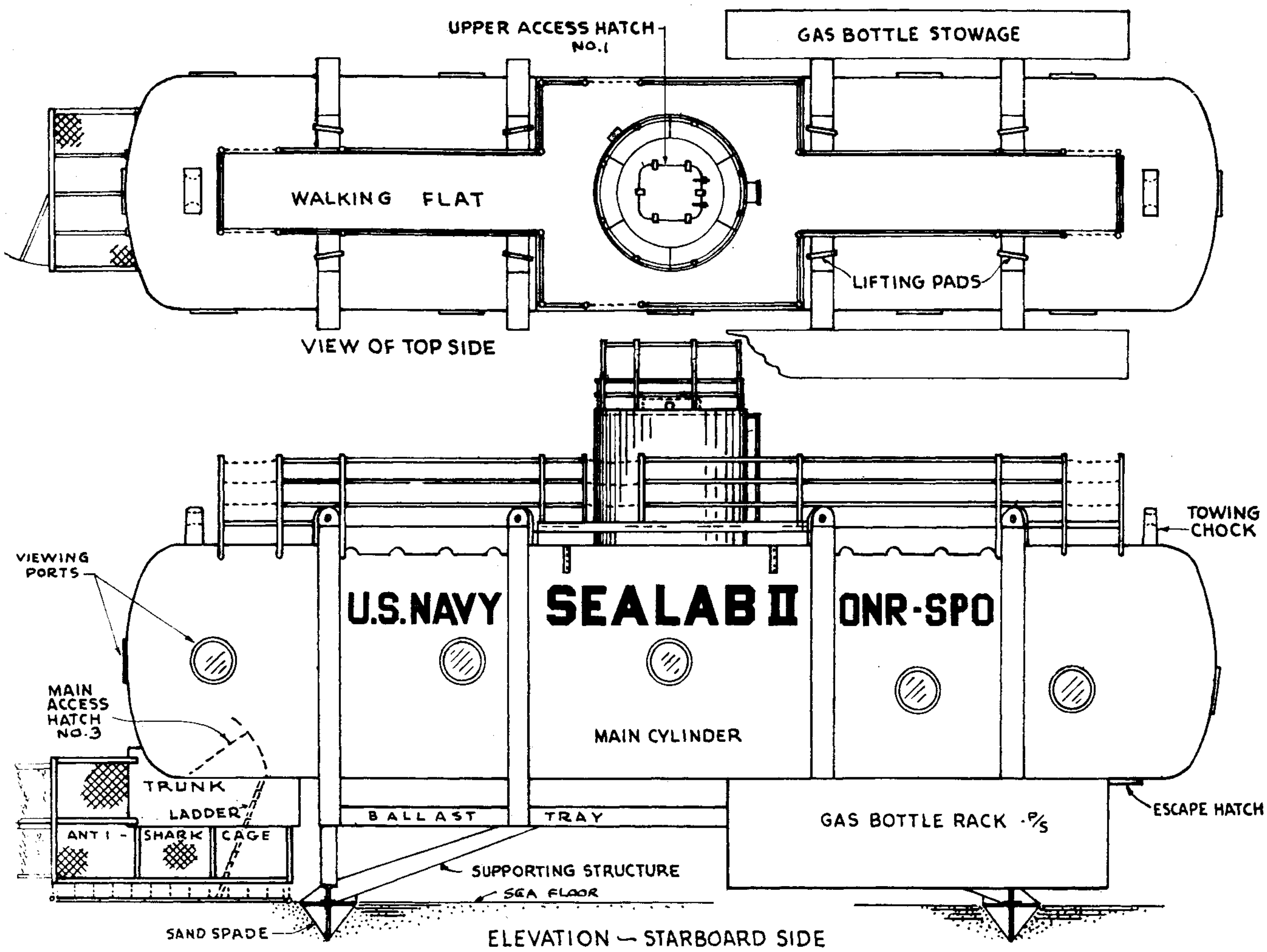

Fig. 1 SEALAB II exterior arrangement.

Submerged Equilibrium and Negative Buoyancy Requirements

A submarine requires variable water ballast to provide it with reserve buoyancy on the surface and to achieve neutral buoyancy in all load conditions while submerged. SEALAB II had the added requirement for proper negative buoyancy while emplaced on the sea floor, so that it would be self-anchoring.

It is interesting to note that neither the U.S. Navy's SEALAB I nor Cousteau's undersea habitats of Continental Shelf Station no. 2 were fitted with scientifically designed ballast tanks. Cousteau[2] wrote of the monstrous and hazardous task his divers undertook in placing over 70 tons of lead underwater in undersea houses to keep them from sliding into the abyss of the Red Sea. The job of removing the valuable solid ballast to retrieve the habitats at the end of the experiment was also a formidable task.

What determines how much ballast water is needed for SEALAB? The answer is contained in the following word equation:

ballast water = reserve buoyancy + water to be blown from skirt + negative buoyancy

The following water ballast requirements were decided early in the design: reserve buoyancy, 25 tons; weight of water in the entrance skirt, 6 tons; negative buoyancy, 13 tons; total weight of ballast water required based on the foregoing word equation, 44 tons. This volume of water was functionally distributed among the four ballast tanks as follows: ballast tank no. 1, 9.5 tons; ballast tank no. 2, 14.0 tons; ballast tank no. 3, 9.5 tons; ballast tank no. 4, 11.0 tons; total, 44.0 tons. In any particular mode of operation, a ballast tank was either completely full or empty. This design simplified control and operations, inasmuch as it became unnecessary to vary the quantity of water in any tank during an operation. Moreover, the ballast tanks could be designed as "soft" tanks vs "hard" tanks.

For a submersible, it is important that the submerged displacement volume be precisely defined and calculated. Based on Archimedes' principle, the weight of the craft in the submerged neutral-buoyant condition is equal to the weight of sea water displaced. SEALAB II's 209-ton submerged displacement was defined as the volume of the hull and all appendages, including the 6-ton volume within the skirt. Hence, the amount of water in the skirt was treated as part of the onboard load.

To give SEALAB II the capability of self-anchoring to the sea bottom by a negative buoyancy of 13 tons, her weight on the bottom, therefore, had to be 209 tons plus 13 tons, or 222 tons. Her surface displacement would then have to be 222 tons less 44 tons of water ballast plus the 6 tons of water in the skirt, or 184 tons. To achieve this, a weight and moment control program was instituted during design and construction. The amount of fixed lead ballast was calculated and installed on SEALAB during construction. She was weighed prior to launching to verify the correctness of weight and center of gravity, which amounted to a dry land "submarine trim dive." Topside variable lead was also included to permit final adjustments in weight and moment to account for outfitting weights. Her calculated weight distribution was as follows: hull weight (including outfit, but less ballast,

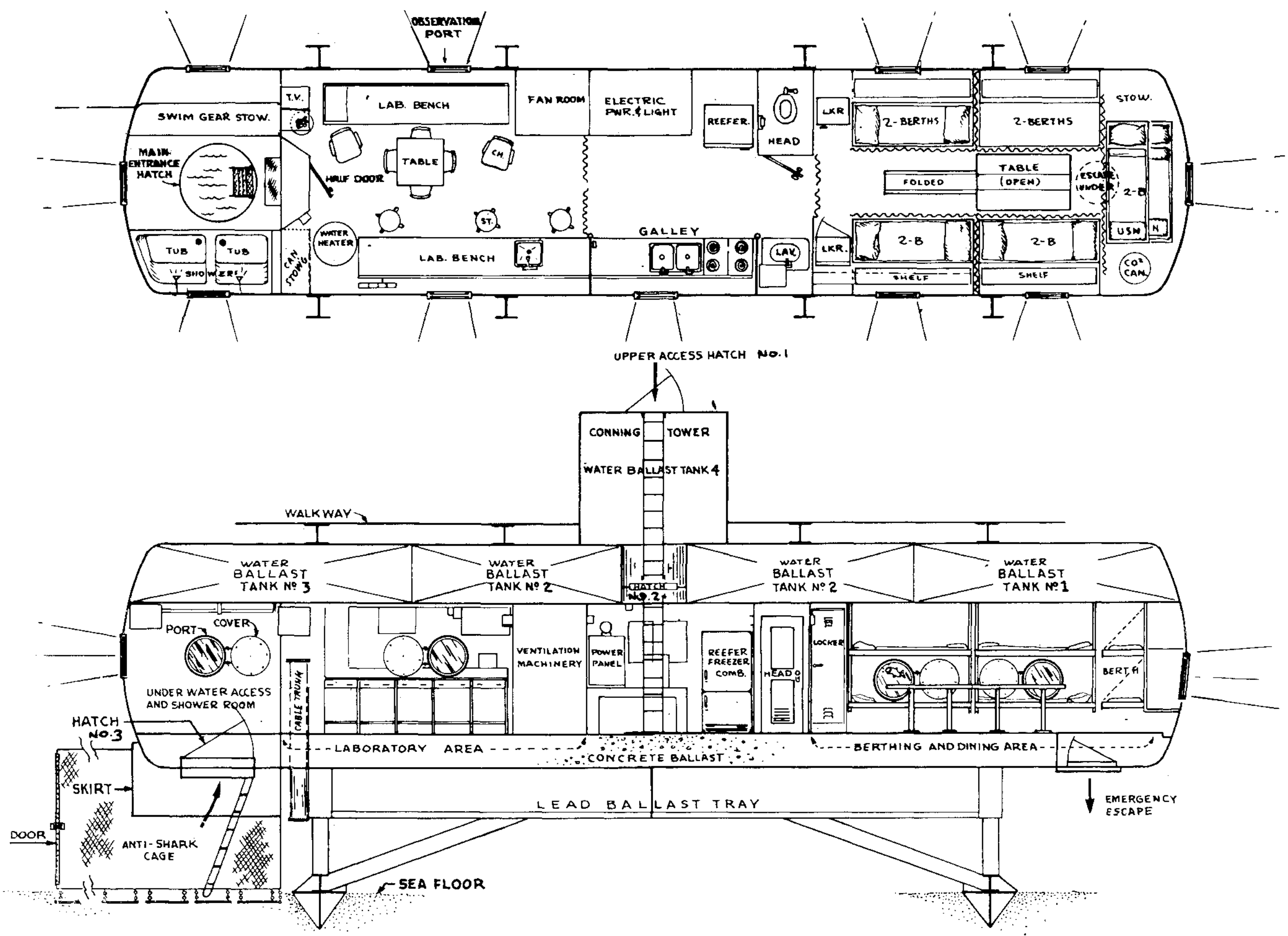

Fig. 2 SEALAB II interior arrangement and section looking to port.

119 tons; fixed concrete ballast, 29 tons; fixed lead ballast, 31 tons; variable lead ballast, 5 tons; surface displacement = total weight: 184 tons.

Operations

Figure 3 demonstrates the function of each ballast tank from SEALAB II's surface condition I to her emplaced condition V. Table 1 is a detailed tabulation of the weight, buoyancy, and metacentric height in each condition. SEALAB II was surfaced by blowing tanks in the reverse order.

Hydrostatic Principles

To achieve a successful design of many fittings, appurtenances, and systems in an MAPH, a clear understanding of the hydrostatic forces involved is necessary. Some of these installations may suffer reversal of loading or pressure, as will be explained below.

Figure 4 shows a cross section of SEALAB II as she floats on the surface. The conning tower hatches are shown open and we have atmospheric pressure within the hull. In this condition, the hydrostatic pressure on the hull is the same as on any surface ship, being a triangularly distributed load that is zero at the surface and a maximum at the keel, corresponding to the hydrostatic head h_1. Each foot of head of sea water corresponds to 0.444 psi. On the surface, therefore, the observation ports experience about $2\frac{1}{2}$ psi external pressure which tends to push the port hole glass inboard.

When SEALAB II is placed on the bottom, as shown in Fig. 5a, the hydrostatic pressure distribution is completely reversed. At the gas-water interface at the bottom of the skirt, the differential pressure is zero. The gas pressure inside SEALAB is higher than the outside sea pressure throughout the hull boundary. The differential pressure is a maximum at the overhead of the living compartment corresponding to the head h_2. This phenomenon becomes clear if we would imagine that a glass U-tube manometer is installed is shown, with one leg of the tube sticking up through the open hatch into the SEALAB living space, and the other leg in the ocean. The constant gas pressure in the living compartment is opposed by the hydrostatic head (Fig. 5b), giving rise to a differential pressure h_2 that is zero at the interface and a maximum at the overhead (Fig. 5c). In this condition, then, we find that the pressure tends to push the port glass outboard at about $3\frac{3}{4}$ psi. From the foregoing analysis, it became apparent that the design of the hull, viewing ports, piping, and wiring penetrations to the hull, hatches, etc. must be designed to withstand internal and external pressures of varying degrees. Sealed nonpressure-proof containers, such as canned products, a water heater tank, hand lanterns, and flashlights, must be vented before the MAPH's submergence or surfacing operations to allow the containers to breathe to avoid damage.

Gas Leakage through Cables

SEALAB II was connected to a surface ship with an umbilical cord which furnished power, communications, and gas. As explained previously, the gas atmosphere inside submerged SEALAB is always greater than the outside sea pressure. Figure 5a shows a typical cable that penetrates the hull. Leakage of gas outward through the penetration is prevented by a gland, or what is popularly known as a

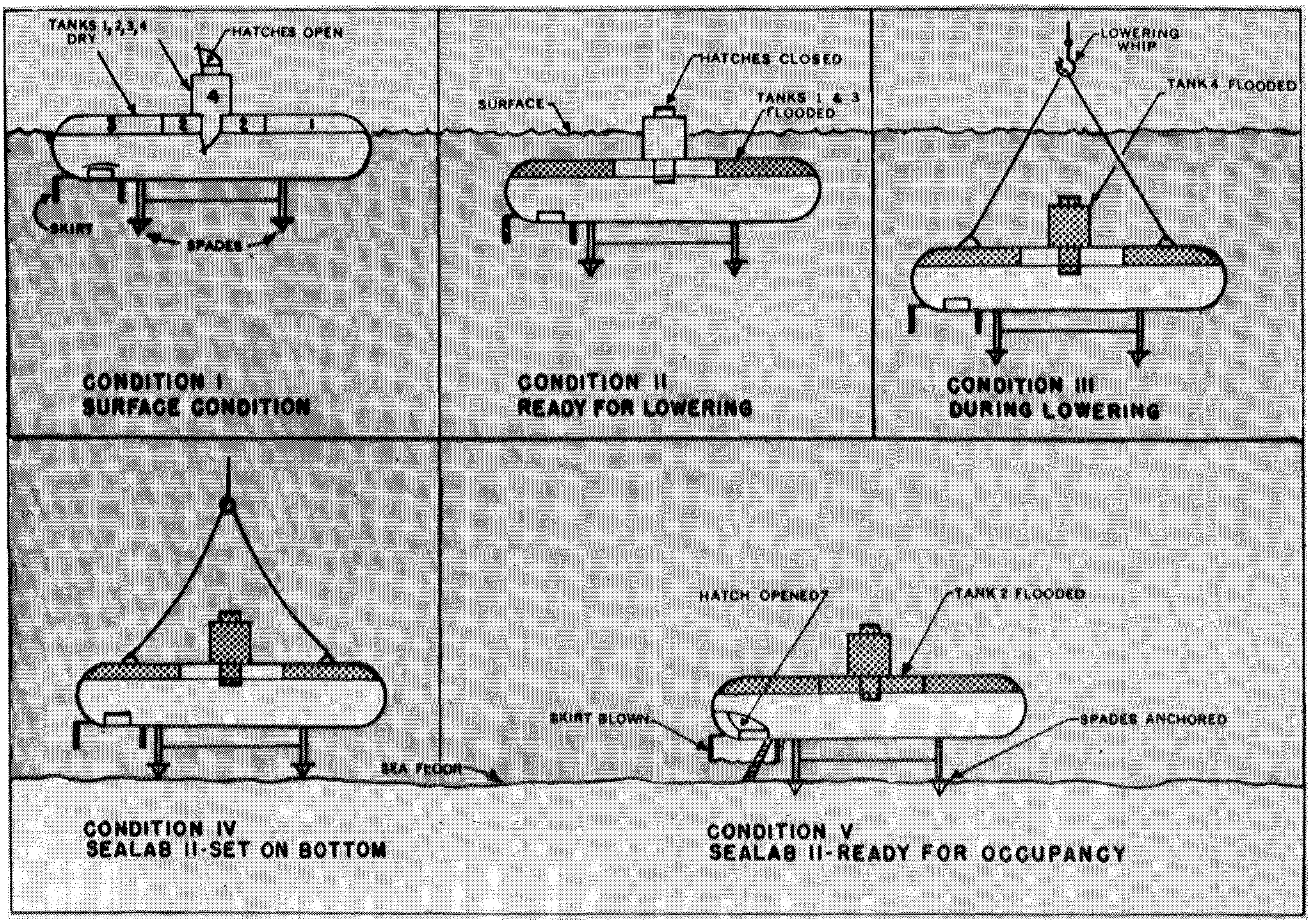

Fig. 3 SEALAB II in various phases during lowering.

stuffing tube. However, if the cable is the usual stranded cable, with two or more conductors, we encounter a serious gas leakage problem even though the stuffing tube is made tight. The reason is that the interstices between strands make the cable act like a hose, and gas can leak right through the cable to the surface. Somewhere between the sea bottom and the surface, the cable jacket or insulation could explode from the high internal gas pressure.

From this analysis, it was decided that all cables in the umbilical cord between SEALAB II and the surface support ship must be effectively blocked internally at the point where the cables penetrate the hull. For the same reason, all hoses and pipes leading between SEALAB II and the surface had to be designed for a working pressure equal to the sea pressure at designed depth.

Hull Structure

Because of operational problems encountered in the SEALAB I experiment, it was decided that SEALAB II should be

Table 1 Weight, net buoyancy, and metacentric height of SEALAB II under various ballasting conditions

Condition		Weight, tons	Net Buoyancy, tons	Metacentric height GM,[a] ft
Condition I	Surface displacement; 20-in. freeboard; all tanks dry	184	+25	2.29
Operation:	Flood tank no. 1 and no. 3	+19		
Condition II	SEALAB II floating at mid-height of conning tower	203	+6	1.87
Operation:	Pressurize tank no. 2 and main cylinder with helium. Flood tank no. 4	+11		
Condition III	SEALAB during lowering operation by hoist	214	−5	2.21
Operation:	Set SEALAB on ocean floor. Flood tank no. 2	+14		
Condition IV	SEALAB on ocean floor. Tank no. 2 flooded	228	19	
Operation:	Blow entry trunk	−6		
Condition V	SEALAB ready for entry and occupancy	222	−13	

[a] Metacentric height is the distance from the center of gravity G to the metacenter M.

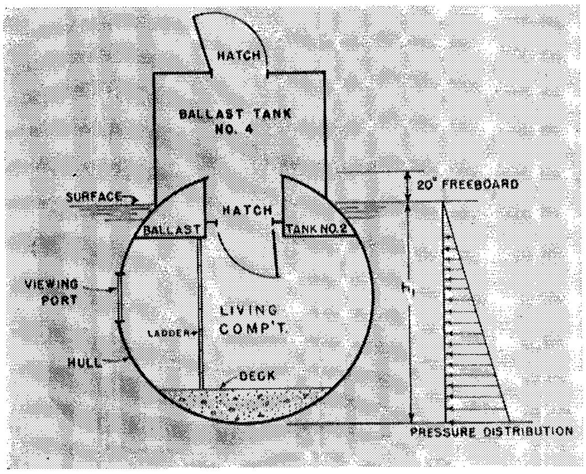

Fig. 4 Hydrostatic pressure distribution on SEALAB II on the surface.

charged with gas to bottom pressure while on the surface. Moreover, it was anticipated that the main habitat might be used as an emergency decompression chamber. She was, therefore, designed as an unfired pressure vessel under the American Society of Mechanical Engineers (ASME) Code for a working pressure of 125 psi and a test pressure of 188 psi. Dished heads for the tank ends were not a design problem, but became a procurement problem; the best supplier of 12-ft-diam, 1-in.-thick steel heads wanted a minimum of 150 days to effect delivery, which was obviously incompatible with production requirements. The shipyard decided to form these by an underwater explosive-forming method. The dished heads were successfully completed in 30 days. A description of this feat, which has been recognized internationally as a first-time accomplishment, is described in Ref. 1.

Drainage System

The main habitat of SEALAB II consisted of a laboratory, galley, bunk room, and washroom. The laboratory sink, galley sink, washstand, and water closet were fitted with a drainage system for gravity flow to the sea, similar to any household drainage system. The simplicity of this design was amazing. An examination of Fig. 5a would make it apparent that the head of water between the P-trap of a fixture and the water level in the skirt is the fall that makes gravity drainage possible.

Hull Insulation

SEALAB II's hull was insulated internally with corkboard 2 in. thick on the shell and 1 in. thick on the over-head. The production schedule was such that a completion air-tightness test had to be done after all hull penetrations and hatches and cork insulation were installed. For this test, the main tank was pressurized to 15 psig. At the end of the test, a tank vent was opened and the pressure quickly released. On regaining entrance into SEALAB, it was discovered that a considerable portion of the cork had dropped off the sides and overhead even though it had been properly cemented to the steel. (A similar experience had occurred in SEALAB I.)

Diffusion of any gas through the cork cell walls depends upon the difference in the partial pressure of the particular gas involved inside and outside the cells and the permeability of the cell wall structure to the particular gas. Cork cell walls are relatively impermeable to air. Under air pressure, the cells would first compress, then re-expand slowly as the air diffuses into the cells. When the tank pressure was dropped rapidly, the entrapped air in each cell could not be released fast enough; therefore the cork literally exploded by expansion. It is believed that, if the tank pressure had been

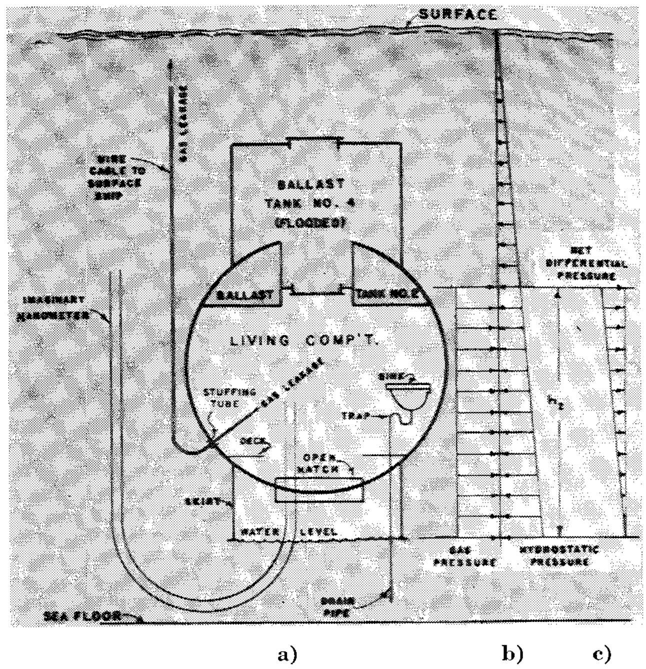

Fig. 5 Differential pressure distribution on SEALAB II in submerged condition.

dropped very slowly, no damage to the cork should have occurred. Significantly, no problems have been experienced when helium was used as the pressurizing gas.

Leveling Problems

SEALAB II was designed with feet so that the sea bottom soil bearing pressure would not exceed 300 psi. It was anticipated that SEALAB II would need adjustable legs to overcome any list or trim caused by a sloping bottom terrain or by uneven settling of the legs. But, because of the austere program in this project, it was decided that adjustable legs would not be worth the price and so no leveling devices were installed. The price, as it turned out, was that SEALAB II did have a 6° port list and considerable trim up by the bow. Scott Carpenter, the lead aquanaut, dubbed her the "Tiltin' Hilton."

A new development will put an adjustable self-leveling device on SEALAB III. This design is similar to the principle of mooring a mine to an underwater clump: the mine has positive buoyancy and floats underwater on even keel, independent of the slope of the sea bed. SEALAB III's main habitat will have positive buoyancy so that she will float underwater on even keel, moored to a special clump spaded to the ocean floor. Restraining wire preventers will keep the main habitat from taking undue trim or list. Internal ballast could be shifted to compensate for any required heeling moment.

Electrical and Electronic Problems

The use of a primarily helium atmosphere in an MAPH at ambient sea pressure creates a host of electrical and electronic problems. At 650 ft depth, this pressure becomes 304 psia. Helium's heat conductivity is roughly six times as great as that of air. This combination of high pressure and high heat conductivity creates some unique problems.

Light bulbs, vacuum tubes, television tubes, and cathode ray tubes may implode at such ambient pressures. Electrical alignment of solid-state circuits may be disturbed. Diffusion of helium into vacuum tubes through the seals could lead to malperformance. Much research and development need to be done before these problems are successfully overcome.

Thermostatic electrical elements that work satisfactorily in air at sea level fail to work in hyperbaric helium atmospheres, primarily because of the difference in heat-transfer rates. Presently, such items as overload relays in motor controllers, thermal trip elements in circuit breakers, thermostatic switches in split-phase motors, and thermostatic control devices in refrigerators and freezers must be eliminated, and other devices substituted.

Blowers, fans, and vacuum cleaners as used in MAPH's present special problems. Since these are constant-volume machines, blowers and fans require proportionately more horsepower in direct proportion to the increase in atmospheric density. At 650 ft, for instance, the density of the MAPH atmosphere could be four times standard air. A 1-hp air-rated fan would require 4 hp to drive it. Electrical motors, on the other hand, could be uprated in power output, because of the superior cooling quality of a helium atmosphere. The amount of uprating depends on motor design and construction.

For increased personnel safety, the electrical system should be isolated from the hull rather than grounded to it. This also reduces galvanic corrosion caused by stray currents between hull and water. While the electrical system is isolated from ground, it is extremely important that the frames of all electrical devices be solidly grounded. All portable equipment should be fitted with an electric cord containing a ground wire to prevent electrical shock to personnel.

Pressure Actuated Devices

Bellows-operated devices, such as high- and low-pressure cutout switches in compressor-condensing units, which respond to the differential pressure between the inside and outside of the bellows, cannot function due to the high ambient pressure.

Bourdon-tube-type pressure gages are designed to read "gage" pressure; i.e., the gage reading would show only the pressure above the ambient. To obtain absolute pressures from gage readings on MAPH's, add the absolute atmospheric pressure inside the MAPH to the gage reading.

Air-Conditioning Problems

The design of an air-conditioning system for an MAPH presently is based on many engineering guesses. Experiments in SEALAB I and II indicated that 90°F and 50% relative humidity presented a fairly comfortable ambient to the aquanauts. Little, however, has been done to determine the "comfort zone" at various pressures. Over-all heat-transfer coefficients, which determine the rate of heat loss from the habitat to sea, remain to be measured. The performance of heaters, cooling coils, and dehumidifiers likewise remain to be tested.

The atmosphere of an MAPH is essentially a closed one in that little gas makeup is required. Carbon dioxide is usually absorbed chemically by substances such as lithium hydroxide; consumed oxygen is replenished from storage bottles. In this light, it is important that the atmosphere be kept free of contaminants. In general, substances that are found unacceptable for use in nuclear submarine interiors are also verboten in MAPH atmospheres. Particular caution is paid to use of proper paints and lubricants. Fluorescent tubes and thermometers containing mercury are considered unacceptable, as breakage could contaminate the atmosphere.

Hull Materials

The preservation of life and equipment in an MAPH depends on the structural integrity of the hull. The atmospheric gas bubble must not be allowed to leak out. The selection of hull materials and welding and other fabrication processes must, therefore, be pointed towards the ultimate certification requirements for a manned submersible.

The Secretary of the Navy has issued SECNAV Instruction 9290.1 of 22 June 1966, "Certification for Safety of Manned, Non-Combatant Submersibles." Reference 3 has been issued by the Naval Ship Systems Command to present the requirements and procedures necessary for U.S. Navy certification of the material adequacy of manned, noncombatant submersibles. In particular, special attention must be paid to the impact and fracture toughness properties over a range of temperatures sufficient to fully define the fracture characteristics of the material for the intended service environment. Inasmuch as this instruction was issued long after SEALAB II was built, and in view of the fact that SEALAB III is a conversion of the SEALAB II, the provisions of this instruction have not been invoked in this craft.

Summary

The foregoing paper describes only some of the problems associated with design of a manned ambient-pressure habitat. Much research, development, testing, and evaluation need to be done before we have sufficient knowledge to fully engineer all phases of an MAPH design. Project SEALAB III, the Navy's undersea experiment designed to evaluate man's ability to live and work for prolonged periods at a depth of 430 ft with excursions to 600 ft, will furnish many of the answers.

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