Saturation Diving System Design Considerations

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At the outset of a saturation diving mission, a selection of the basic diving system to safely accomplish the tasks involved must be made. The main components, deck decompression chamber (DDC) and submersible decompression chamber (SDC), are designed as conventional pressure vessels, though special attention is now being given to hatches, viewports, and electrical penetrations due to constraints imposed by personnel habitation requirements. Where divers have to be transferred between chambers under pressure, a reliable chamber mating system is essential. A rationale is offered for the design of such critical components as the SDC umbilical and high-pressure breathing gas storage and distribution systems. In the water, diver safety is very much dependent upon the face mask. The development of an optimum full-face mask, incorporating hard wire communication, is described. In conclusion, human engineering and psychological considerations are presented. These offer to show how the designer can have a significant influence on the state of mind of the diver and operator and make both safer on the job.

I. Introduction

WHEN we think of exploiting the ocean, there is, of course, no absolute limitation with regard to depth. Westinghouse has built free and towed vehicles to operate at depth up to 20,000 ft and there are more to come. However, man's greatest harvest of the seas will be in the regions where man can range most freely, leaving his vehicle or shelter to observe, touch, and work with the objects surrounding him, his body exposed to the ambient water pressure.

It is now widely recognized that conventional diving, with decompression in the water following every work period, is uneconomical except for short duration shallow dives. The alternate, saturation diving, has the diver resting, eating, and sleeping at a pressure very nearly equal to the water pressure at the work site. Each mission must be evaluated on its merits; at depth in the region of 200 ft, even a score of man-hours of work on the bottom will justify the use of saturation diving.

The Westinghouse "CACHALOT" system was the first saturation diving system used on a commercial diving project. This was at Smith Mountain Dam, Va., August to December 1965. Apart from the purely economic advantages of the CACHALOT diving system, the proximity of a gas-filled chamber to the underwater work site enhances diver safety in a number of ways. The submersible decompression chamber (SDC) provides a refuge for the diver if a malfunction occurs in his life-support system. It is important to recognize that this refuge is at the diver's saturation pressure. For a saturated diver, a rapid dash to the surface would mean a painful case of the "bends" and almost certain death.

II. System Selection

Having decided that a saturation dive is needed, we have a large variety of saturation diving systems from which to choose. If activity is limited to one spot on the ocean floor, an obvious choice would be a bottom mounted habitat, such as those used by the U.S. Navy for the SEALAB series of experiments. In this case, the divers live and work on the ocean bottom 24 hr a day. This poses a logistic problem and leaves the divers relatively remote from surface-based help in case of emergency.

The first saturation diving system built by Westinghouse, named CACHALOT I, had the divers eat and sleep in a large pressure vessel mounted on deck. We call this the deck decompression chamber (DDC). The trip to the work site on the ocean floor is made in a smaller pressure vessel, the submersible decompression chamber (SDC). The SDC remains with and supports the divers by supplying breathing gas, power, light, quality communication, and special tools.

To give an idea of size, the DDC of CACHALOT I consists of two adjacent main chambers each 7-ft i.d. × 10 ft long. A mating flange at one end permits a pressure-tight connection to be made with a similar flange on the SDC. At the opposite end, a 5-ft i.d. × 5 ft 6 in. long entry lock provides technicians and medical personnel with access to the DDC under pressure. Connecting hatches between main chambers and main chamber to entry lock are 30-in. i.d. The SDC is a single chamber, 5-ft i.d. × 8 ft 9 in. high, with a main hatch in the bottom dished end, 27-in. i.d. An artist's sketch of the system in operation atop Smith Mountain Dam is shown in Fig. 1. The depth rating of CACHALOT I is 450 ft.

Compared to a bottom mounted habitat, we now have greatly enhanced mobility. Also, for most of the day, divers are very much more accessible to surface personnel for surveillance and aid when needed. When a task calls for only one or two divers, our MINOLOT DDC is employed. This is a scaled-down version of the CACHALOT DDC with only a single main chamber 6-ft i.d. × 7 ft 6 in. over-all length. It is designed for 850-ft operation.

For research work and evaluation of new equipment we do our diving on terra firma, where controlled conditions enhance both safety and experimental validity. Our hyperbaric complex at the new Ocean Research & Engineering Center on the Chesapeake Bay at Annapolis will be completed this summer. It comprises three connected, almost spherical chambers, rated to carry internal pressure equivalent to 1500 ft of sea water. The entry lock and main chamber are at grade level, and the "wet" chamber, providing a water depth up to 6 ft 3 in., is housed in a basement room one floor below.

When a diving site requires the services of a large number of divers, a deltic decompression chamber arrangement, such as is shown in Fig. 2, becomes attractive. While providing isolation for sleeping shifts, this gives the safety of 9 separate chambers to the diving team. A single central SDC serves all chambers.

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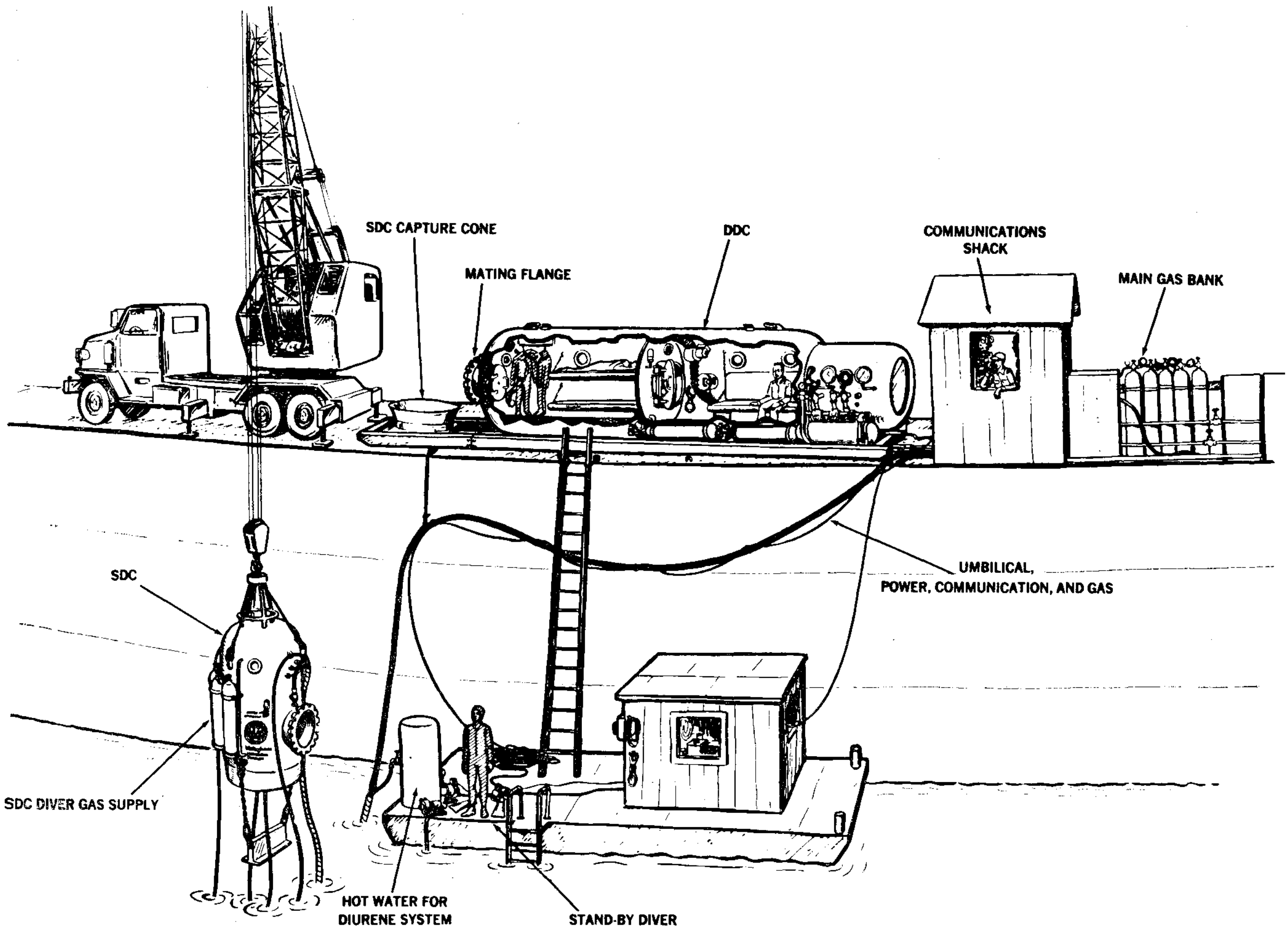

Fig. 1 CACHALOT I saturation diving system.

III. Chamber Mating Devices

When the saturated personnel must be transferred from one chamber to another, a mating system is required to make a pressure-tight connection between the two chambers. When the pressure in both chambers is exactly the same, hatches can be opened to the connecting passage and personnel can be transferred without being subjected to a pressure change.

There are almost as many mating devices as there are saturation diving systems. The functions required for the mating device are: align, bring together, and seal. As is so often the case, the simplest possible device is reliable and safe and does the job best.

On our CACHALOT I system, we use a 20-in.-diam, 300-lb ASA flange with bolt holes slotted out to the flange periphery. The same size flange, but now rated to 400 lb ASA, serves our CACHALOT II system. At a rated pressure of 377 psig, the 12–$1\frac{1}{4}$-in.-diam A193B7 bolts are stressed to under 11,000 psi, compared to the yield stress of 105,000 psi. To make bolt positioning quicker and more certain, we have changed to swing bolts, as shown in Fig. 3. Note that the bolt torque is carried by a little cube riding in the flange slot and that the pivot pin does not carry the sealing load.

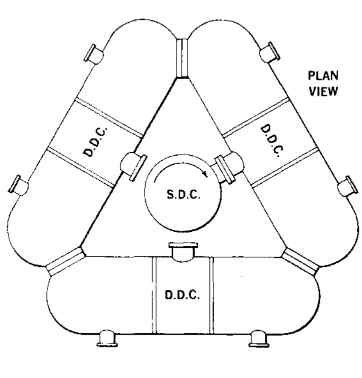

Fig. 2 Deltic decompression complex.

If it is desired to save the 2 min required to tighten flange bolts, a GRAYLOK clamp arrangement, manually or power operated, can be used. This generally requires better initial alignment of the SDC. Our practice is to lower the SDC into a shallow capture cone, which can be seen in Fig. 1. This insures vertical and transverse alignment. The final maneuver is to roll the SDC and capture cone towards the DDC by means of four rollers carried on two rails. This can be accomplished manually or by using a hydraulic ram.

The British Navy, a French company, and at least one American company have systems in operation where the mating flange is on top of the DDC and the SDC is lowered onto it. Depending on the geometry chosen, substantial forces can be applied to the mating flange and trunk when the system is used on a rough sea. The design of the flange and trunk must concern itself with these forces, as well as the static sealing forces.

IV. Pressure Vessels

Aside from the very important fact that human lives depend on pressure integrity, the design of decompression chamber shells follows a well-established procedure. In this country, the guide lines are provided by the American Society of Mechanical Engineers (ASME) Code, Sec. VIII, for unfired pressure vessels. The code rests on a very broad foundation of practical experience, stretching back to 1911. It provides very simple guidelines for a conservative design and carefully spells out an inspection and test procedure which insures that the design intent is actually met. Because pressure vessels are traditionally associated with hot steam, there is a need to be watchful of low-temperature operation requiring attention to criteria not fully covered by this code. Before being placed in service, pressure vessels must be subjected to a hydro test at $1\frac{1}{2}$ times the intended design pressure.

For a thin-walled, cylindrical pressure vessel welded and internally pressurized, the wall thickness minus corrosion allowance t is given by

$$t = [pr/(SE - 0.6p)] \text{ in.} \quad (1)$$

where p = design pressure, psi; r = inside radius, in.; S = maximum allowable stress, psi; E = joint efficiency, typically 80–85%.

At the ends of a cylindrical shell, where a double curvature surface generally forms a closure, bending and shear stresses arise due to the differing amounts a cylinder and the double curvature surface would expand if not joined together. These discontinuity stresses are typically only 5 to 15% over the circumferential stresses in the cylinder and are considered as blanketed by the general factor of safety in the code.

A somewhat similar condition arises where a heavy flat bulkhead is used to separate adjacent chambers. We prefer such an arrangement over a dished separation, since more usable space is gained within a given envelope.

For shells subject to external pressure, the mechanism of failure is more complex. Thin shells fail due to instability, where a small deflection worsens the load condition. The ASME Code for unfired pressure vessels also covers this type of loading. The approach makes for very simple, step-wise design calculations, demanding the very minimum of familiarity with stress analysis.

The operative word for safety in this area is care. Care is looking for and correcting faults in plates, care in watching minimum thickness in spun end caps, and care in welding.

V. Pressure Hull Openings

The largest openings used on decompression chambers are hatches through which divers must pass. Since hatch covers and seals become heavier and costlier with size, a compromise is necessary. Where frequent passage is envisaged, 30-in. clear diameter works very well, as may be seen in Fig. 4. For the less frequently used hatch in the base of the SDC, we settle for 27-in. i.d., and the mating trunk, used only twice per work shift, is 19-in. i.d. All hatch covers used by us thus far are of the flat, pressure sealing variety. Although there are situations where a single cover, sealing against pressure in both directions, would be attractive, we are not ready to abandon the inherent safety afforded by a self-sealing cover.

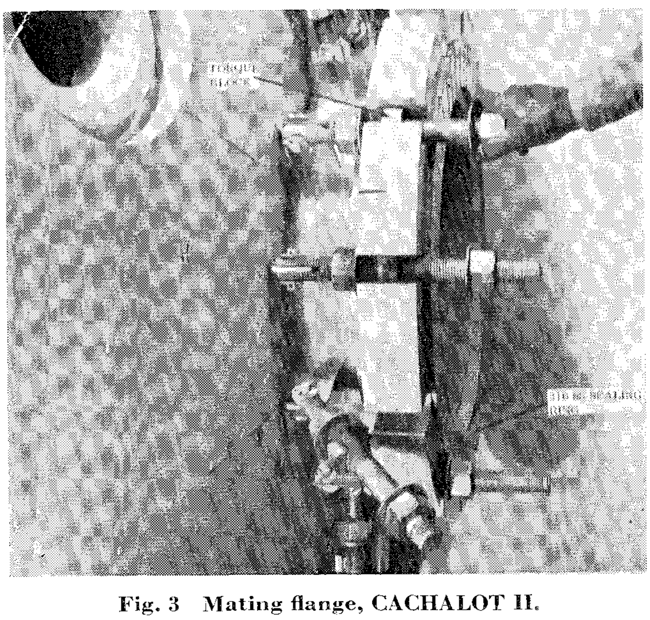

Fig. 3 Mating flange, CACHALOT II.

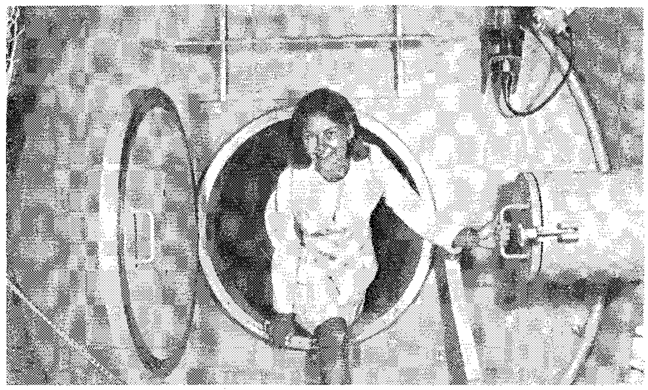

Fig. 4 30-in.-diam pressure sealing hatch.

An essential feature on any deck decompression chamber is an entry lock, to admit medical personnel and technicians to a main chamber under pressure. For the passage of small items needed during normal operations, from pencils to CO_2 absorbent, a provisioning lock saves breathing gas and time. Should a medical emergency occur inside the DDC, this smaller lock serves to exchange instruments and medical supplies in a quick and convenient manner.

Coming down further in size of openings brings us to the universal adaptor plates, 6- to 10-in. diam provided to carry miscellaneous electrical instrument penetrations and/or small hydraulic and gas sample lines. These are simply flat plates sealed against the inner end of a cylindrical nozzle welded into the shell. They provide the flexibility demanded by varying service or research conditions. More significantly, such adaptor plates remove the temptation to drill and weld on the chamber in the field, which can result in a very dangerous situation.

Although TV monitoring is extensively used in our field today, viewports are still an essential feature on a manned chamber. We find a 5-in.-diam clear area adequate. For the ultimate in safety, our in-house facility, rated for a 1500-ft depth equivalent, has viewports of laminated construction. Two pieces of $1\frac{1}{4}$-in. tempered pyrex glass are used, each piece individually capable of carrying the full chamber pressure.

To get an electrical signal or power line to the inside of a pressure chamber, an electrical feed-through or bulkhead connector is employed. A great variety of patterns are commercially available to function both in air and under water. The common feature is an electrical conductor fed through an insulator in such a manner that a pressure difference can be sustained by the joint.

This critical joint is made differently by different manufacturers. A company offering small transducer glands takes the classical approach of squeezing the insulator onto the bare conductors in a conical cavity. Neoprene and Teflon are used to bracket the temperature range $-300°$ to $+500°F$ up to 10,000 psi. Lava, which crushes to a powder upon compression, may be used to $+1800°F$. This design yields a very simple and compact hull feed through for low voltage lines.

One of the larger companies in this field manufactures a wide range of submarine cable and bulkhead connectors and completely engineered cable assemblies. The electrical conductor within the connector has a knurled flange, which, after sandblasting and surface coating, is encapsulated in a contact insert made of Novalak, a thermosetting plastic. The contact insert in turn is carried within the connector casing, which can be of stainless steel or plastic. We use a 40-pin bulkhead connector receptable and mating cable connector plug of this type for the data link on our CACHALOT II SDC.

Connectors that can be plugged and unplugged under water are the specialty of a small California company. The plug and socket resemble the household equivalent in shape. They come as one-, two-, three-, or four-pin neoprene mouldings. The "pin" is a neoprene rod carrying one or two stainless steel collar pieces arranged along its length. The conductor leads are encapsulated in the neoprene, their ends soldered onto the collar pieces. The socket carries mating collars and is similarly constructed. Pins are slightly larger at their outer ends than the mating hole, thus producing a beneficial wiping action under water.

The sealing methods described thus far have relied on a compression seal or elastomers bonded to the conductors. A different tack is taken by a company from Framingham, Mass. Conductors are made of one of the sealing alloys such as Niron and sealed into a metal puck by fusing sintered glass preforms at 1900°F. The puck is typically made of 316 stainless steel and sealed in the housing of the connector by means of O-rings. Choosing the correct glass and alloys insures the glass is kept under compression after cooling, thus giving a chemical and mechanical bond. By comparison, the leads used on light bulbs and television tubes have a matched seal, where expansion of glass and metal are very similar.

By their very nature, the materials used in this type of connector are stable and give almost indefinite service when correctly applied. They are designed to withstand up to 20,000 psi in one or both directions. We have used such connectors successfully on our CACHALOT systems and on our DEEPSTAR series of research submersibles.

For simplicity, the language used so far has been applicable to bulkhead connectors. The same principles can be and are being used on feed-throughs where a pig tail is soldered to the conductors on one side and then potted. Where service conditions permit, feed-throughs are preferable and less prone to failure in service, although we have seen attempts with stranded conductors which are singularly unsuccessful.

The art of sending an electrical current through a metal pressure bulkhead is relatively old, but the widespread need to use such a device in a marine environment is quite recent. Understandably, failures on test and in the field are still quite frequent. Our principal interest here is with failures in the field and these can be of three kinds: 1) loss of signal, 2) mechanical failure causing a pressure leak, and 3) a burn-through from an exterior fire.

Connectors dripping with sea water frequently lose signals from high-impedance circuits. The sea water is often ubiquitous, so the best cure is a designed wiping action on engagement. When disengaged, thin pins protruding beyond a guard often get bent, making re-engagement impossible. Flimsy elastomer moldings when flexed in service can break internal soldering connections and thus produce an open circuit on a connector which looks quite normal.

Many of the standard commercial through hulls are made to depth ratings substantially in excess of today's diver depth. In consequence, a leaking fitting is usually an O-ring problem. However, siting of connectors should consider the possibility of impact damage, especially on the SDC.

A burn-through from an external fire is more likely on a neoprene feed-through than with a connector. Where a high-oxygen atmosphere exists on the inside of the chamber, this hazard cannot be ignored.

Any hole made in the pressure hull weakens the structure both because of the material removed and the stress concentration attendant upon a discontinuity. The treatment used for any but the smallest openings is the area replacement method. This essentially requires that the metal section removed in cutting the hole be replaced by a welded nozzle adjacent to the hole inside and/or outside the pressure vessel. Where pipe nipples or flanged fittings are welded into a hole in the $\frac{1}{2}$- to 3-in.-diam size range, the fitting itself is usually ample reinforcement. The area replacement method and its constraints are fully discussed in Sec. VIII of the ASME Code for unfired pressure vessels and will not be detailed here. Very small drilled and tapped holes, with diameters less than about half of the shell thickness generally may be used without any reinforcement. With these, as with any openings in a pressure shell, the spacing should be such as to avoid ligamenting the vessel wall, especially along lines perpendicular to a principal stress.

VI. Materials

Unless an unusual weight problem exists, the modern fine grained, killed mild steels are very satisfactory for heavy shell members, hatch covers, and general framing. These have a much improved fracture resistance compared to the old mild steels of similar carbon content. They are inexpensive, easy to form, weld, and machine, and, with today's protective coatings, corrosion need not be a problem. Where stress levels warrant, medium carbon and alloy steels can be specified, the selection depending on both stress levels and operating temperatures.

Price and availability are important considerations seldom covered by the text book. For example, pricing an 84-in.-diam ASME flanged and dished head earlier this year showed that the finished article in an aluminum killed medium carbon steel came to only 43% of the cost of a similar head in HY-80, despite the fact that forming costs on the lighter gage HY-80 were substantially cheaper. As is normal with the less common materials, it was required that a minimum batch of 3000 lb of plate be purchased in HY-80. To insure the pressure integrity of the SDC, mating and hatch sealing surfaces in contact with sea water are clad with rings of 316 stainless steel $\frac{1}{4}$ in. thick.

Valves and high-pressure piping may be of carbon steel, brass, stainless steel, or monel, depending on the fluid carried and the location and function of the item. We made extensive use of steel valves, schedule 80 seamless steel pipe, and forged 3000-lb fittings in our gas distribution system, operating at 2400 psi. Where maximum safety is required on a high-pressure, pure-oxygen system, monel is specified because of fire risk. Even at the relatively low pressures engendered by the use of open circuit, pure oxygen during decompression, a fire hazard exists. The best policy is to keep oxygen content in a manned chamber below 25%, but, since even the best equipment can malfunction, insulators, plastics, paint, and furnishings have to be chosen and located to minimize fire risks.

The volatile constituents of cements and paints can constitute a safety hazard. Even though the maximum rate of out-gassing occurs in the few hours following painting, vapors are generated for much longer periods than the average user would suppose. Research work initiated as a result of studies on nuclear submarines have produced cross-linkable latex paints which are excellent where severe abrasion is not anticipated.

On the inside of our pressure chambers we use a base coat of DIMET COAT #6, which is an inorganic zinc silicate, a second coat of AMERCOAT #86, which is an organic hybrid, and a fine coat of AMERCOAT #50, which is an epoxy ester enamel. A minimum drying period of 10 days at 70°F or over is recommended before a chamber is put into service.

Divers will at times carry atmosphere contaminants into a decompression chamber, either in their pockets or amongst their personal belongings. Hair oils, aerosol cans, and spray remedies for colds and headaches are best left outside the

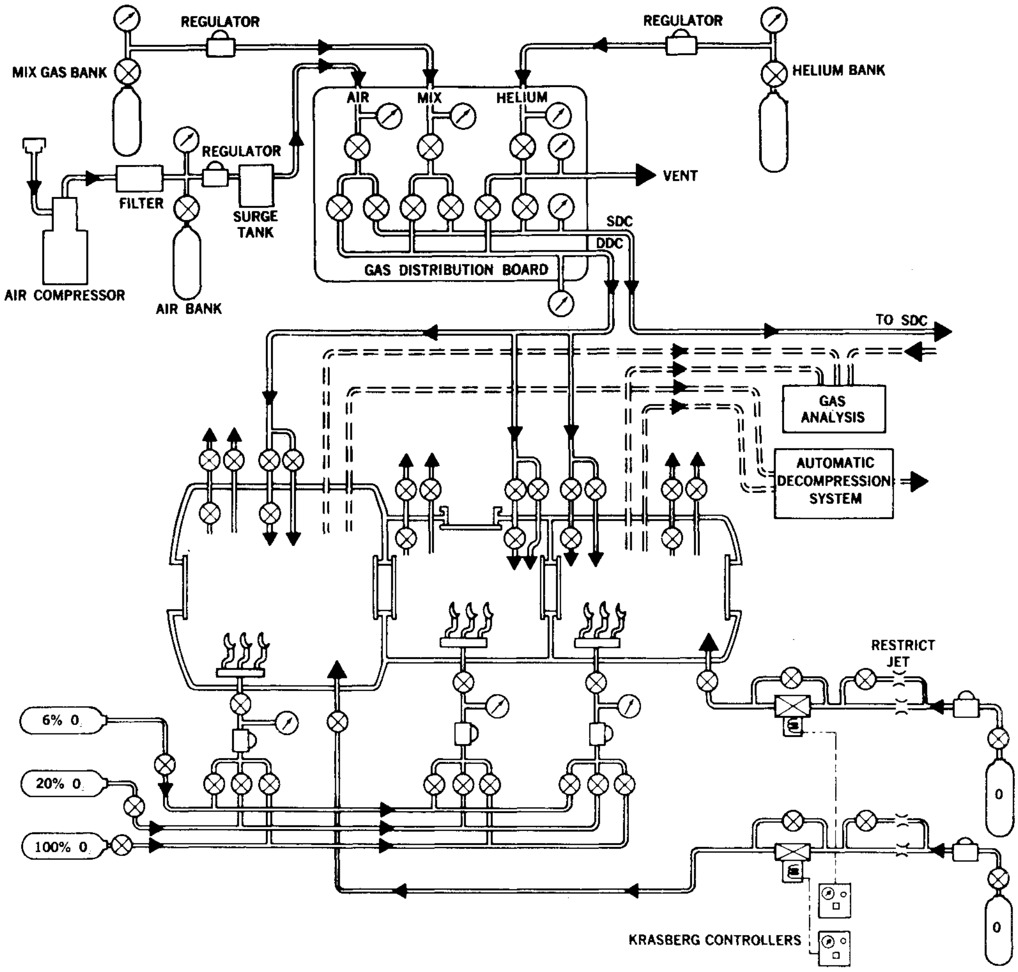

Fig. 5 Breathing gas piping schematic.

chamber. We have a kit inspection for divers where the guiding spirit is: "if in doubt, leave it on the outside!"

Experience on SSN's shows that the bulk of carbon monoxide found in the atmosphere originates from cigarette smoking. To stay below the safety limit of 25 ppm CO, a catalytic burner would be required as well as an electrostatic precipitator, to remove aerosols generated. We do not feel this elaboration justified and do not allow matches or smoking in decompression chambers.

An unusual problem arises when TV cameras are used in high-pressure helium atmospheres. The thin glass of the vidicon tube is relatively permeable to high-pressure helium, and failures were experienced due to helium getting into the vacuum space. Better sealing methods have now alleviated this problem.

VII. Breathing Gas

Because a man's endurance without the life-giving oxygen in his breathing gas is measured in seconds, this part of the diving system demands fail-safe design and stringent quality control during manufacture. Actually, although the list of hazards is long and varied, a complete loss of breathing gas is almost unheard of in today's saturation diving.

Let us look at what the breathing gas system must do. We are typically involved with four common gases: air, heliox (sometimes called "mixed gas"), helium, and oxygen.

Bulk storage is usually in 240 std. ft^3 cylinders at 2400 psi. The requirement then is to reduce pressure and to distribute the right gas to the point of need. Admission and discharge rates must be controlled to yield the desired time-pressure profile and the oxygen content in chambers and breathing bags must be monitored and controlled. To accomplish all this, six distinct subsystems are provided: 1) main gas admission and vent system, 2) bib-system, 3) metabolic oxygen system, 4) gas analysis system, 5) automatic decompression system, and 6) SDC and diver gas system.

Space does not permit even a cursory description of each of these subsystems. The abbreviated schematic shown in Fig. 5 depicts the surface portion of the total system, i.e., items 1 through 5. The following will give a brief rundown on the functions of each subsystem together with the hazards peculiar to it.

1) Main Gas Admission and Vent System

This system moves and stores relatively large volumes of gas, to charge and vent the DDC and SDC. Most of the bulk gas storage is associated with this subsystem. For handling convenience, we prefer to have gas cylinders in racks of 12. These racks are grouped and manifolded in banks, so arranged that each type of gas is available from at least two independent blocks, which can supply and be recharged independently. A gas distribution board controls the routing of the gases from bulk storage, but the final valve controlling admission to a chamber is mounted adjacent to a viewport right on the chamber being charged. As may be seen from Fig. 5 and Fig. 6, we have 100% redundancy on main admission and vent through-hulls for each chamber. Additionally, the back-up line is valved on the outside only, which insures that control of this vital function cannot be usurped by a panicky diver.

Though not a part of the same subsystem, provision locks need to be designed to prevent accidental chamber venting.

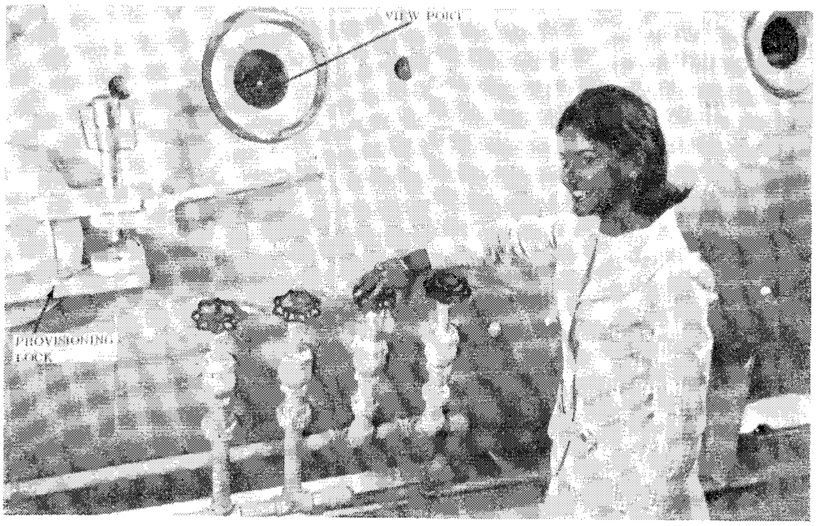

Fig. 6 CACHALOT II main admission and vent valves.

We mount a pressure gage immediately adjacent to the equalization valve of each provision lock, having found that divers may call an inner cover closed when it is open. If the closure on the outer cover is such that it could be opened under pressure, a mechanical interlock is desirable, preventing this until the equalization valve is in the "vent-to-atmosphere" position.

2) Bib-System

In order to speed up loss of inert gas from body tissues, divers breathe pure oxygen during certain stages of decompression. The bib-system supplies this via separate oral-nasal masks, so that the chamber as a whole need not be charged with this more hazardous gas. Such an arrangement also gives greater flexibility should it be desired to cycle divers on a number of gas mixtures.

If the atmosphere in a chamber becomes contaminated, the usual practice would be to evacuate divers to an adjacent chamber while decontamination is affected. Should this be impossible or if all chambers are contaminated, divers can then use the bib-system for emergency breathing until one chamber is readied for them.

3) Metabolic Oxygen System

An adult male performing only light work and sleeping for 8 hr out of 24 will consume a little under 2 lb of oxygen to satisfy his daily metabolism. I would hasten to add that for a great many reasons, this is not a simple consumption figure. To begin with, the greater portion of this oxygen is exhaled in the form of CO_2 and there are large variations between individuals and hourly variations with a given subject.

Our metabolic oxygen system is designed to automatically feed the correct amount of oxygen into the two main chambers of the DDC. A Krasberg pO_2 sensor puts out a voltage signal proportional to partial pressure of oxygen in the chamber. When this falls below a predetermined level a solenoid valve is opened to admit more oxygen. A second Krasberg unit is provided for back-up. This normally performs a purely monitoring function, activating an alarm set slightly outside the "normal" operating limits. The human body reacts more violently to an excess of pO_2 than it does to anoxia. To stay out of trouble at that end, we have a further safeguard in series with the Krasberg controllers. This consists of a pair of restrictor jets in parallel so sized that the smaller will pass normal minimum oxygen requirements and the larger one a little more than the normal maximum required by six divers. The latter occurs on decompression when the percentage oxygen is being raised. Such a design approach ensures that almost any conceivable malfunction or operator error will not produce a critical pO_2 level inside the chamber for many hours.

4) Gas Analysis System

To give a check on atmosphere status inside a manned chamber, gas samples should be drawn and analyzed with laboratory type instruments at regular intervals. The type of test and frequency are dictated by the nature of the dive—commercial or experimental. Our practice on working dives has been to monitor pO_2 and pCO_2 in the DDC continuously and log the values once per hour. In the SDC a reading is taken prior to and after each dive.

5) Automatic Decompression System

At the present time an error in decompression is much more likely to arise from human ignorance than from system malfunctioning. Unlike the admission of metabolic oxygen, this function has only one dangerous boundary, viz, too rapid decompression. We currently use a pneumatic analog for our automatic decompression control. A servo module will open a solenoid vent valve when the main system lags behind the analog. Even when on automatic decompression, the duty watch will monitor chamber pressure and efflux rates. In case of system malfunction each chamber can be manually vented as previously described.

6) SDC and Diver Gas System

The SDC receives only mixed gas from the umbilical, controlled either by the divers or the gas distribution board. The divers in the water draw mix from two banks of cylinders mounted externally on the SDC. Normal residence time in the SDC is short enough not to require metabolic oxygen makeup. An unforeseen extension can be handled by having the SDC occupants breathe from either or both of the external gas banks. Should these be exhausted, any desired gas can be routed down the umbilical hose by connecting appropriate cylinders to the gas distribution board. This makes the submerged endurance of the SDC practically unlimited.

VIII. Umbilicals

It can be truly said that the best umbilical is no umbilical of any kind. The hurdle at present is lack of an economical power source for underwater use in the 25- to 75-kw range. There is a tantalizing abundance of oxygen in the sea itself, as well as energy rich hydrogen. We do have one key to this treasure and we do use it on SSN's, but the price is over 5 kw hr per pound of oxygen.

Great strides have been made in umbilical design in the last three years. CACHALOT I had a bundle of individual wires and hoses taped together with friction tape. For CACHALOT II, a second generation system with an 850-ft depth capability, power and signals are taken to the SDC in separate cables, each one sheathed and terminated for extension in 500-ft lengths. The hoist cable, hot water, breathing gas pneumo-fathometer, and current for external lights are still taken to the SDC by individual hoses and cables. Everything except the hoist cable is again taped together to form a single unit.

Safety and operating ease would both be greatly enhanced if all the functions of hoist and umbilical cables could be combined in a single unit, within the smooth envelop of double helical armor cable. The technology and equipment needed to produce such a cable exist, but the high unit cost associated with small quantities has militated against full exploitation of the potential. This is surely an area where industry and pertinent U.S. Navy activities could join in a combined effort with resultant benefits to all concerned.

Our current safety policy requires that saturated working divers be tethered. We use hard wire communications to the divers as a part of his umbilical. Breathing rigs used so far have been of the semiclosed style, requiring only one gas line from the SDC to the diver. In cold water (and most water is cold at depth) a hot water line is added to supply the diver's Diurene wet suit. This was a Westinghouse development. Power for a light carried on the forehead and a pneumo-fathometer hose complete the umbilical.

For CACHALOT I, diver umbilicals started off in 50-ft lengths. After the first contract, this was increased to 100 ft, with the last 25 ft tied off at the SDC, to be used only with special permission. For our last contract, at Narragansett Bay, only 50-ft lengths were permitted. Very obviously the length of diver umbilical which can be handled with safety is very much dependent on local environment. The ideal is to design it to be slightly negatively buoyant. As with the main SDC umbilical, a combined unit in a smooth sheath will enhance safety and lend itself to handling by a powered reel.

IX. Diver Equipment

The expression "diver equipment" is generally applied to those portions of the total system carried by the diver. These include: exposure suit; swim fins, when used; weight belt; knife or other hand tools; face mask; microphone and earphones; breathing rig; and protective helmet, when used. All of the preceding bear critically on diver safety and well being. All of them share the feature that man and the system have a very intimate interface here. Our design approach can best be illustrated by a few words on the evolution of face masks.

The best way to obtain a seal between a breathing gas system and a man is via a rubber mouthpiece supported between the teeth and sealed by the lips. We use this mode for the backup gas supply regulator, normally clipped to the diver's chest. The main difficulty with this type of seal is that a man cannot enunciate clearly with a mouthpiece between his teeth. We are thus led to a gas-filled cavity surrounding the diver's mouth and nostrils, with a microphone supported some $2\frac{1}{2}$ to 3 cm in front of the lips. A little flap interposed between the lips and the microphone is advantageous for cutting out the hissing spikes from the sound spectrum. Flexible rubber breathing hoses with large, light action nonreturn valves have to be led into this cavity.

Moving up to the eyes now, the need is to interpose a gas space between the cornea and the water with a flat, glass surface essentially perpendicular to normal forward vision. The refractive index between water and cornea tissue is such that water bearing directly against the eye will cause incoming rays to focus well behind the retina, leading to a blurred image. A clear cone with a 95° included angle erected on

Fig. 7 Full face mask.

each eye, leading to a $4\frac{1}{2}$- to 5-cm-diam flat glass disk satisfies the need in minimum space. Tempered safety glass is heavy and a gas space is very buoyant in water. The ideal mask would be neutrally buoyant, alone, or in position on the face. In practice, we have to compromise here. Further, if the individual eye pieces do not remain in one plane, the images seen by the two eyes will shift relative to each other and visual acuity suffers. This consideration and ease of cleaning and defogging make a single eye piece attractive. A mask arrangement with a one-piece lense is shown in Fig. 7.

Turning to seals, two distinct areas are involved. For cold water operation, the mask must cover the full face, which means keeping the water outside a line running high across the forehead, curving down towards the jaw hinge and sweeping under the chin. A second seal is required to keep CO_2 build up to a minimum in the small space outside the lips.

For the primary water seal, the simplest method is the reverse fold as currently offered on the rubber skirts of the Scott and Desco masks. In the hope of fitting more faces with a given size, we are experimenting with a liquid filled seal.

Less stringent than the primary seal, but geometrically more complex, the closure surrounding the oral-nasal cavity can be effected with a soft elastomer, spread over a relatively large area. It must be comfortable on this softer and more mobile region of the face and still prevent significant gas exchange with the relatively dead space in front of the eyes. For "slithering" this seal into position, we provide two external bosses under the eyes, so configured that a wet, gloved hand can readily grasp them. The same bosses play a part in purging the mask, a feature we will now examine.

Under the general heading of purging, a number of quite distinct capabilities are needed. Although we design to exclude water, the possibility of some getting into the mask must be provided for. The following lists the purging requirements of our face mask: 1) on descent, admit gas from oral-nasal to eye space; 2) on ascent, bleed gas from eye space to oral-nasal; 3) admit water to eye space to flush fogged lense; 4) purge water from eye space; and 5) purge water from oral-nasal space.

To pressurize the eye space on descent two small passages with rubber flap valves are moulded integral with the body of the mask. These provide a one-way channel from the oral-nasal cavity to the eye space; the wearer's face forming one wall of the channel. When the pressure in the eye space is significantly above ambient, the lense will tend to lift away from the face taking the upper portion of the oral-nasal section with it. This will allow gas to escape from the eye space to the oral-nasal space.

To flush the inside surface of the lense the diver rests face down in the water, body sloping up towards the feet. A finger is then used to break the primary seal just above the temple to admit a small shot of water. To purge water from the eye space or the oral-nasal space small purge valves are used. Three are shown in Fig. 7, though two will suffice with a one-piece lense. They are provided with a push button manual override but should not be set to open at a δp in excess of 50—100 mm Hg is a real "lung-buster" for most men. It should be remembered that water in a gas space is as much under the control of gravity as tea in a cup, regardless of the ambient pressure. The purge valves must be located with this in mind.

The consequences of failure in a face mask are too obvious to need reiterating here. The step-wise process of identifying the various functions is the best road to satisfying them with the simplest and lightest hardware possible. On diver equipment especially, weight and displacement are highly critical. Simplicity is a good feature on anything that goes to sea.

X. Human Engineering

To realize the scope for human engineering in saturation diving, one need only look at some of our working divers or climb through a half dozen decompression chambers. The starting point of all human engineering is to recognize that everything we design, from needles to battleships, has an interface with man. This interface is obvious on a face mask, less obvious on a pressure light fixture until you bang your skull on it or squint at a subject against its glare. The next step is to look at homo sapiens for what he is and then to design the system to suit him, as well as the more abstract requirements typically called out on a contract specification.

Only a few typical areas will be touched upon here. A saturation diving complex abounds with valves. Where these are manually operated, they should have ample clearance for fingers round the operating wheel, and be located for easy handling. Those shown in Fig. 6 are between waist and chest on an average man. Viewports located on the equator of an 8-ft-diam deck chamber would look neat and symmetrical on a drawing, but give backache to anyone but a midget trying to peer through them. We have a little articulated cardboard man in the department who helps us guard against this type of pitfall.

On a control board the layout of valves and gages should be logical, preferably placed on a schematic of the system being controlled. If an action illuminates a warning light, it should be visible from the point where the action was initiated and the point where corrective action must be taken. Since light bulbs can burn out at any time, critical subsystems should be served by dual lights, one to indicate normalcy and one to indicate the abnormal. Even with an expert crew, a color code applied to cylinders, lines, and valves to identify various gases is an aid to safety.

In conclusion, I would like to mention an area often neglected, chiefly because it never shows up on a drawing and the damage done is indirect. This area is noise, defined as an unwanted and generally random sound pattern.

Wherever men are performing a demanding task, noise will tire and distract them and make speech and audio signals less intelligible. When a large amount of energy has to be suddenly released, noise may be inevitable, but there is little excuse for blasting sleeping divers out of bed just to make up a little gas lost when mating the SDC. If you wanted to make a diver nervous, and unsafe, you could hardly do better than produce somber clanging noises every time a hatch cover is secured. Since many of these effects are quite difficult to visualize in the tranquility and comfort of an air-conditioned design office, there is a strong case for giving the young designer a taste of the sea.