Safety in the Cachalot Saturation Diving System Operations

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The Cachalot Saturation Diving system has proved itself much safer than normal deep sea diving; however, the saturated diver must be kept under pressure. A sudden return to one atmosphere of pressure would be fatal. This paper treats, 1) the handling of the saturated diver living in a pressurized chamber at the surface, 2) transferring from there to the underwater work site, and 3) working in the hostile underwater environment. Six divers at a time live in a 26-ft-long, 7-ft-diam chamber. Methods for control of oxygen and inert gas partial pressures, heat, humidity, and contaminants are discussed. Two divers leave the main chamber and enter a diving bell which takes them underwater to the work site. This bell must be handled so as not to endanger the lives of the divers. We must, however, achieve maximum underwater work hours. Problems of handling the bell in rough weather and protecting the vital supply, communication, and monitoring lines are discussed. Divers exit from the bell through a hatch in the bottom, but remain connected to it by 100-ft umbilical lines. In case of any emergency, the bell provides a nearby haven for safety.

I. Introduction

THE Cachalot Saturation Diving System permits six divers to work at depths to 600 ft for 6 hr at a time without the necessity of daily decompression. For the divers, it is physiologically the same as living underwater at ambient pressure.

The divers stay under a gas pressure nearly the same as the pressure of the water where they work for one week at a time. Two divers at a time go down and spend about 6 hr working underwater, and the remainder of the day they are in a large pressurized chamber called a DDC (deck decompression chamber).

The DDC remains on the deck of the work vessel. Divers are transferred by a second chamber [the SDC (submersible decompression chamber)] to and from the underwater work site. They are kept under a nearly constant pressure during the transfers. Any variations in pressure must be closely controlled and recorded in order to prevent decompression sickness.

The SDC is closely monitored and controlled by the topside crew.† It is raised and lowered by a crane and supplied with breathing gas, communications, heat, and power through a bundle of lines called the SDC umbilical. When the SDC reaches a depth where the water pressure is the same as the gas pressure inside the SDC, the divers can open the hatch in the bottom of the SDC. When the two divers exit from the SDC, they are attached to it by another smaller bundle of lines called the diver's umbilical. This supplies communication, gas, and heat and serves as a safety line back to the SDC. At any sign of mechanical or environmental trouble the diver need only return to the SDC for a haven of safety.

This system has been in use for over 5000 underwater man-hours, and has proved itself much safer than normal deep sea diving methods. There is, however, a constant potential of multiple fatalities if pressure should suddenly be lost from one of the chambers the divers use. This paper covers 1) protecting the diver against loss of pressure in his chambers; 2) maintaining a breathable gas for the divers; 3) transferring the diver from living quarters on deck to work site underwater; and 4) working in the hostile underwater environment.

Some of the problem areas in using this arrangement for diving are as follows. 1) The two crews of "topside" operating personnel must maintain, 24 hr a day, a critical awareness for the safety of the divers. 2) Once the divers are under pressure, they can be returned to normal or surface pressure only through a slow, controlled reduction in pressure. 3) The divers, while not underwater, all breathe and rebreathe the same gas which must be circulated and treated to keep it breatheable. 4) Communication with the divers is always difficult as it must be done via radio and when the divers talk they produce helium speech which is difficult to understand. 5) The divers develop an independent attitude which sometimes hinders control by the "topside" supervisor. 6) The divers themselves may lack an understanding of the principles of saturation diving and lack an appreciation for the danger of their situation. 7) Suspending diving operations due to weather or mechanical difficulties is costly. The lives of the divers are the paramount consideration; however, the maximum underwater work hours possible must be achieved.

II. Surface and Inner-Aquatic Support Requirements

A. Installation

The Cachalot system is transported by three tractor-trailer trucks. The DDC is the largest single piece of equipment. It is a 26-ft-long cylinder 7 ft in diameter and weighs about 15 tons. The first contract for Cachalot required working from the top of a dam. Equipment was set up atop the dam and the divers were lowered to trash gates on the dam 140–190 ft underwater. All other jobs have required location on a derrick barge. When at sea, the DDC and all support equipment must be welded or in some other way made fast to the deck. Otherwise, equipment might break loose during a storm, slide into the DDC, and cause damage which could result in a sudden pressure drop for the divers. By the use of equipment modules and custom-made multiple conductor cables and connectors, installation and equipment check out can be completed in about 24 hr.

B. Homeostasis

Homeostasis refers to the ability of the human body to maintain a fairly constant internal environment in the face

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† The SDC is much like an elevator, carrying divers up and down from work vessel to the underwater site.

of wide variations in external environment. External environment of the divers must be maintained within certain limits by the topside crew. One of the big advantages of the Cachalot system over actually putting divers underwater to live is that the divers environment is so much easier to control when they are separated from the topside crew only by the pressure hull of the DDC.

1. *Food, water, and supplies*

A service lock on one side of the DDC provides easy access to the divers for hot meals and supplies. Frequent usage of the lock, however, decreases pressure somewhat in the DDC.

2. *Breatheable gas*

1) Breathing Resistance: A mixture of helium and oxygen is valved in to pressurize the chambers. This gas is lighter than air and presents less breathing resistance at increased pressures. At increased levels of breathing resistance, many men have a tendency to underventilate their lungs, thereby increasing the blood level of CO_2.[1] When the diver is in the water the increased breathing resistance of his diving apparatus must be considered. We have worked without ill effect at pressures to 600 ft with breathing apparatus especially designed for that depth.

2) Oxygen: Oxygen must be supplied to the DDC as it is metabolized by the divers. A Krasberg pO_2 sensor is located in each compartment of the DDC, in the SDC, and there is one in each Cachalot underwater breathing apparatus (CUBA). Oxygen is admitted into the DDC after a drop of only 0.0035 atm by a Krasberg sensor and solenoid valve. Thus, only small quantities are supplied at a time and these go in through 4-ft lengths of perforated tubing to prevent the formation of pockets of high oxygen content. High concentrations of oxygen are a fire hazard and if breathed by the diver would probably cause convulsions if the pO_2 were high enough.[2] Failure to admit oxygen would, of course, be fatal after the existing O_2 was depleted. DDC oxygen content is also continuously analyzed by a Beckman C3 oxygen analyzer located in a gas shack.‡ Oxygen can be supplied to the SDC from the surface when needed as a helium-oxygen mix used normally to increase pressure in the SDC. Should this source fail, the divers have access to their diving gas which is stored in cylinders attached to the SDC. The Krasberg pO_2 monitors on the CUBAs produce a read-out topside which is constantly observed while the divers are in the water. An audible alarm sounds when the pO_2 goes too high or too low and the radio talker can advise the diver to return to the SDC. Anoxia (lack of oxygen) is the divers most dread disease, as it gives no warning. The diver loses consciousness before he can take any remedial action. When using the CUBAs the divers receive a constant flow of helium-oxygen mix from cylinders attached to the SDC.

3) Carbon Dioxide: Failure of the CO_2 absorption system in the DDC would probably produce labored breathing, headache, weakness, nausea, confusion, and finally unconsciousness.[3] A constant flow of gas from inside the DDC is analyzed by a Beckman C3 CO_2 analyzer. Faulty absorption of CO_2 in the DDC and SDC can be traced to one or more of the four following causes: 1) diver failed to replace a canister when scheduled to do so or replaced a canister with another old canister, 2) CO_2 absorption canister improperly filled, 3) obstruction to gas circulation, or 4) faulty gas duct connection. CO_2 absorption canisters are located in each of the two main compartments of the DDC, in the SDC and in each CUBA. Canisters in the CUBAs are changed after each dive; others are changed every 24 hr. CO_2 at normal levels is especially critical during decompression as evidence indicates this is conducive to decompression sickness.[4]

4) Contamination: Since the divers rebreathe the same gas in the DDC for a week at a time, contamination is of particular importance. Sudden contamination is provided for in the DDC by an emergency breathing system designated BIB. The BIB system consists of an adequate number of oro-nasal face masks supplied with an appropriate helium-oxygen mix from outside the DDC. These are left on at all times so that, in any emergency, fresh breathing gas is readily available to the divers. Such an emergency might take the form of a smoke-producing fire. Unknown products or elements are not permitted inside the DDC in order to prevent a gradual contamination. The effects of breathing small or trace amounts of some gases, under pressure, is unknown. *Threshold Limit Values* published by the Conference of Governmental Industrial Hygienists, Pittsburgh, Pa. is used as a guide in deciding what elements to permit within the chambers.

3. *Hygiene*

A shower is located inside the SDC and divers are encouraged to take a soap and hot water bath after each dive. A sink with running water and a toilet are provided inside the DDC.§ Water must, of course, be supplied at a pressure greater than the intra-chamber pressure. Caution must be exercised in design and operation of exhaust systems to avoid inadvertently decompressing the chamber. All exhaust systems should have a control on the outside so that the operating crew has the "last word" in closing a line. Divers must be reminded to clean up spilled food to avoid the build up of unwanted micro-organisms inside the DDC.

4. *Temperature and humidity*

Heat is supplied to the divers by pumping hot water at surface pressure through heat exchanger coils in the gas circulation system of the DDC. This can be thermostatically controlled and each of the two compartments heated individually by varying the volume of water flow.

Humidity is a critical item for personal comfort. A system for dehumidifying the gas and exhausting the accumulated water has been installed in Cachalot and has proven quite satisfactory.

5. *Intra-chamber pressure*

Helium-oxygen (80–20 mix) is admitted to the DDC to begin a diving work week. Caution must be exercised when admitting 100% helium as this is not a breatheable gas until it is mixed with the existing oxygen in the chamber. After the desired pO_2 is reached with helium-oxygen, helium is added to achieve the desired storage depth.¶

One man in the topside crew is designated as the DDC watch. He must make hourly log entries and protect the divers against sudden or gradual loss of pressure. The DDC is composed of two compartments plus an entrance lock. If a leak should occur in one compartment, divers can step into the adjoining compartment and seal off the leaking compartment.

6. *Psychology*

Critical to the success of any diving operation are the attitudes and morale of the divers. Morale is usually ex-

‡ The gas shack provides an air-conditioned enclosed floor space of 4 × 6 ft and houses all gas analysis equipment. This is located next to the DDC communication box and a watch is kept here 24 hr a day.

§ These are modified pullman coach accessories.

¶ Storage depth is the least intra-chamber pressure which will allow effective work at the depth called for by the work. The divers become saturated or "stored" at that depth.

tremely high but may drop to discontent or frustration rapidly if the diver feels he is cut off from the outside and being neglected. Failure of the heating system or other mechanical problems which impose additional hardships on the divers can be expected to lower morale rapidly.

The divers tend to feel isolated from the "outside" crew and may develop independent attitudes. Whether or not the pressure or high partial pressures of helium in the body contribute to these psychological changes is not known. Air cannot be used as a pressurizing agent as divers develop depth narcosis in the presence of high partial pressures of nitrogen.[4]

7. *Wet diver environment*

The diver in the underwater environment maintains homeostasis with very little additional risk over his counterparts in the DDC. There is no appreciable change in ambient pressure, he receives a constantly renewed fresh breathing gas, body temperature is maintained by a hot water "bath," and he does not run the risk of sudden decompression in the event of damage to the DDC. His only threats to homeostasis come from 1) a panic or other situation resulting in an ascent to the water's surface, 2) mechanical injury from the SDC or falling wreckage, 3) injury from dangerous marine animals, and 4) mechanical failure of the CUBA.

C. Decompression sickness

Decompression from depth is always accompanied by a small risk of decompression sickness.[5] The Cachalot diver decompresses only once a week and he is living in a recompression chamber. Thus, in the event of a "hit" (decompression sickness) recompression is always prompt and to date successful.

D. Breathing gas and power

Standby pallets of helium and helium-oxygen mix remain connected at all times to the gas distribution board. From there we can supply air, helium, or heliox to 1) the DDC through a short length of low pressure hose or 2) to the SDC through a low-pressure hose whose length may be 600–1000 ft. Caution must be exercised in the handling of high-pressure gas cylinders, especially those containing oxygen.[6] Power is supplied through hull fittings into the DDC for lights and for "scrubber" motors. These motors circulate the atmosphere through the CO_2 removal, heating and dehumidifying systems. The SDC umbilical supplies power and gas (among other necessities) to the SDC. The following list of the component parts of the SDC umbilical helps to show the complexity of supporting this chamber under water (this list does not include the support cables themselves, which are separate): 1) breathing gas to the SDC, 2) power for the inside lights and scrubber motor, 3) power for the outside lights, 4) hot water for the divers, 5) communication with SDC, 6) communication with no. 1 diver, 7) communication with no. 2 diver, 8) pO_2 monitor for diver no. 1, 9) pO_2 monitor for diver no. 2, 10) pO_2 monitor for SDC, 11) pneumo-fathometer line for diver no. 1, 12) pneumo-fathometer line for diver no 2, and 13) TV camera cable.

Handling of this umbilical can be quite a problem, since with increasing length, simple manpower is not enough and mechanical assistance is necessary. It must be guarded from abrasion or snagging as it "goes over the side."

III. Man/System

A. Introduction

One aspect of saturation diving which is similar to space travel is the isolation of the diver. He is confined to the chamber system or underwater areas of comparable pressures until such time as he undergoes the lengthy decompression procedure necessary to bring him safely back to one atmosphere. If fire breaks out, or the atmosphere becomes contaminated, or the diver becomes sick, he cannot leave the chamber system. We can, however, keep the DDC diver under close visual observation and send medical aid in immediately if the need arises. This provides a safety factor that ocean bottom dwellings do not have. The doctor, however, may not take his patient to the hospital until decompression is complete.

B. Selection and Training of Saturation Divers

Divers with any signs or symptoms of claustrophobia must not be selected as saturation divers. The diver must live for a week at a time inside the DDC and must unhesitatingly head back into the SDC in an emergency. Divers must have the intelligence and background to be able to perceive the dangers of saturation diving. They must be trained so that safety procedures are almost a conditioned response and so that they understand the principle of saturation diving enough that they can react appropriately to unforeseen circumstances.

C. Selection of Operating Crew

Topside operating personnel in the Cachalot system are, for the most part, qualified divers themselves. Operating personnel must also be emotionally stable, able to get along with others, and able to react with a cool head to an emergency situation.

The normal tour for the topside crew is two weeks at sea and one week off. As is evident from the large percentage of this paper devoted to surface and inner aquatic support requirements, the responsibility for the safety of the operation lies largely with the topside operating personnel.

A very real threat to continued safety in any potentially dangerous operation is the complacency that develops with continued success. The operating crew must be selected from conscientious personnel and must never be allowed to forget their important responsibility.

D. Face Mask Seal

Achieving a face mask that will seal effectively on all divers' faces has been a safety problem. The CUBA uses breathing bags and a full face mask. If the face mask does not seal, gas leaks out which is expensive and may exhaust his gas supply prematurely. In addition, if gas leaks out, water may leak in. If water gets into the CO_2 absorption canister, a baralyme solution is formed. If this "juice" is present in sufficient volume it may work into the diver's inhalation hose and be taken into his mouth. It produces a burning sensation and an acrid taste. Divers are introduced to this taste during training in order to guard against a panic producing situation. A diver with baralyme "juice" in his system must head for the SDC for safety. The baralyme solution produces no permanent ill effects.

E. Doffing CUBA

The Cachalot underwater breathing apparatus is so constructed that, in an emergency, the diver could remove the apparatus by himself underwater. This is a "last resort" safety feature. Should the diver's umbilical become hopelessly entangled or trapped by falling debris, he can quickly remove his CUBA and either breathe from his partner's emergency regulator or swim back to the SDC holding his breath.

F. Communication

Communication is seriously hampered in the helium atmosphere the divers must breathe. The resonancy of human speech is changed markedly, producing the now familiar

"Donald Duck" effect. Trained personnel can understand the helium speech of divers, they are familiar with it at depths of 200–300 ft. Fortunately, topside communication comes in clear to the diver. Yes and no questions can be asked of the diver and on standard diving operations there is not likely to be a significant communication problem. At depths below 200–300 ft or even at shallower depths where the diver must communicate, an unusual phenomenon, helium speech, presents a difficult procedural and safety problem.

The most promising approach to the problem is that of the helium-speech unscrambler. This device gives an instant replay of the divers voice with changes which make the speech audible. Early models of this were not too satisfactory, but these are being improved.

G. Fire Hazard

The fire hazard in a closed chamber varies directly with the percent of oxygen in the atmosphere. Chamber atmosphere is maintained at 0.35 atm which is 8.7% at 100 ft and 2.7% at 400 ft. These O_2 percent will not support combustion fast enough to generate a flame. Also, helium conducts heat away so fast that it is more difficult for high temperatures to be reached.

The principal fire hazards lie 1) in the method of replacing the O_2 metabolized by the divers and 2) during the O_2 breathing phase of decompression. When the divers breathe pure O_2 during decompression, they exhale into a breathing bag which is vented through the DDC pressure hull to the outside. Thus, a build-up in O_2% in the DDC is avoided and the fire hazard is negligible.

IV. Man/Environment

A. Dangerous Marine Life

The principal problem we have experienced with dangerous marine life is one of economics. When sharks begin to show unusual curiosity or signs of aggressiveness, the divers retreat to the SDC and wait for the sharks to go away. This causes some loss of productive time so that an effective shark repellant would be useful to have if such were available. Sharks have appeared rarely, though, only 3 or 4 times in our total of 5000 underwater manhours.

The barracuda is a potentially quite dangerous fish but in practice we have had only one bad encounter. This happened when a barracuda struck at the shiny emergency mouthpiece on the front of the CUBA rig. (We have since covered these over with black tape.) The diver was not injured.

B. Operating in Heavy Seas

As weather and sea states build up and the work vessel responds to wave action, the SDC lifting boom goes through a corresponding movement, which in turn sets up movement in the SDC. This movement is usually the criterion for suspending operations in heavy weather. It is dangerous for the divers to enter and exit the bell when it might be revolving in a 10-ft-wide circle and making 6-ft vertical excursions.

One solution to this problem is to lower the SDC through a well in the middle at the work vessel as shown in Fig. 1. This virtually eliminates any transfer of roll and pitch motion to the SDC. Motion would still increase as sea states increased, but, by the time SDC motion became objectionable, the vessel would probably be dragging anchors from the heavy seas. The problem can also be approached with a strain relief system, or by anchoring the SDC from the ocean floor. The final answer to working in heavy weather is to have ocean-floor-based installations independent of any surface support vessels.

C. Fouling Umbilicals

The divers umbilical is a necessity and a hindrance. The diver would be much more free to work if he were independent or the SDC. However, it would be fatal if he became separated from the SDC and could not find his way back. That is, he could not go to the surface as this would be fatal and, if independent of the SDC, he would have a limited gas supply.

D. Visibility and Current

Underwater work in warm, "gin clear," still water can be an exhilarating experience. Unfortunately, very few contracts are let for work under these conditions. Most contracts require work in cold, black water in a current. This can be a living nightmare of frustration and fear for the divers. Even though professional divers are accustomed to working under adverse conditions, topside personnel must be aware of the increased risk and be alert for ways to assist the divers. Decreased visibility increases chances of the diver being struck by projections or falling debris. Lines may become fouled and returning to the SDC in an emergency is more difficult. Black water increases the chance for panic in a diver. Cachalot operations run 24 hr a day, so night diving is a standard part of the operation.

Severe currents make swimming and staying in one position underwater a job in themselves. Being lowered to the site in the SDC eliminates one danger of swift currents. However, in a severe current there is always the danger of a diver losing his grip, being swept against an obstruction, having his mask knocked off, losing consciousness, and drowning in just a few minutes.

Work must be suspended when conditions become too severe. The divers cannot be subjected to too much risk, regardless of financial loss to the contractor. A good diving supervisor may take over the job of radio talker when conditions underwater become dangerous in order to give the divers all possible support from topside.

V. System/Environment

A. Lines Suspending SDC Part

A 2300-lb anchor is attached to the SDC for each descent. The SDC is positive by about 500 lb without this anchor. If all lines to the surface should part, the divers can release the anchor from inside the SDC to achieve positive buoyancy and return to the surface where they can be retrieved.

B. Keeping the SDC Position Stable in Currents

This was accomplished by putting a line from the SDC to a winch on the upstream corner of the work vessel. By adjusting the length of this line, the SDC could be positioned up or downstream in the current. Current was kept in line with the vessel's long axis by shifting anchors. On a relatively small work vessel we had telescoping booms erected at the corners of the work vessel in order to increase the angle and purchase from the deck to the SDC. As working depths increase, this becomes a greater problem as the tugger line approaches 90° and will raise the SDC rather than pull it into the current.

C. Lifts over DDC

The derrick barge personnel are always informed of the seriousness of damage to the DDC and are not permitted to make any derrick lifts over the DDC while it is occupied by saturated divers.

D. Emergency Situations

1. Power loss

Emergency hand lights are provided inside the SDC and loss of scrubber motor function would not be critical for several hours. The divers are instructed that, if necessary, they should exhale through their diving canisters to remove CO_2 from the atmosphere.

2. Communication loss

In the event of a loss of communication at a depth beyond surface diver capability, the divers will make ready for the ascent, seal hatch 1, and then signal topside that they are ready to come up by blowing out three bursts of gas from the SDC vent valve. This is one reason the divers must be able to operate the system without instructions from topside.

3. Loss of surface gas supply

A loss of the regular gas supply is not critical as the divers have access to the diving gas cylinders on the outside of the SDC which would sustain them for several hours.

4. Collision with underwater object

The principal concern here is to be assured that no damage has been done which will cause the SDC to leak at or on the way to the surface. Accordingly, any damage should be inspected by either the saturated divers or, if the SDC was on the way up when it happened, we might choose to have a surface diver go down to inspect the damage.

5. Fire on the work vessel

In the event of fire on the work vessel the divers must be given instant consideration. The only way to get them off of the vessel in a hurry is to put them all into the SDC and lower it over the side where it is cool. Here another vessel can take over the suspension activity if necessary. Diving gas would supply oxygen for a few hours but CO_2 removal would be a problem. If possible, additional baralyme would be sent in so the divers could spread this around to absorb CO_2.

VI. Unanticipated Safety Problems

A. SDC Umbilical

Mention has been made of the problems encountered with handling of the SDC umbilical. A somewhat different and intermediate solution is described here. When using the large boom of a derrick barge to lower the SDC, a manilla line was made fast to the SDC umbilical about 75 ft back from the SDC. This line was passed through a block on the side of the boom and then to a winch on deck. As the SDC was raised the umbilical could be raised also and lowered over the side by careful operation of the winch. Although this was completely effective for only the first 75 ft of descent by the SDC, it took the main weight of the handling process off the deck crew and they were able to handle the umbilical much more carefully. On one occasion the umbilical was snagged going over the side and power was lost to the SDC. This cuts off light and the scrubber motor in the SDC. It would take at least 8 hr for a substantial build-up in CO_2, and emergency hand lights are provided inside the SDC for this situation. The SDC can always be returned to its cradle and "remarried" to the DDC while repairs are being made.

B. Electrical Lines and Connections—Source of Sporadic Problems

A faulty readout on the pO_2 dial or loss of radio contact had to be traced to a break in the line. If the connection at the diver hook-up point was sound, the break could be anywhere in the 500 ft of line going from the diver to the SDC and through the main umbilical to the radio shack. The main points of wear were 1) on the first 30 ft of diver's hose where the divers pulled them over wreckage and 2) in the 100- to 200-ft length of the main umbilical where wear was most frequent.

C. Severe Ear Infections

Ear infections are a constant source of problems on any diving operation. Keeping the humidity down in the DDC is a great help, but ear infections still occur. An ear wash solution should be used after each dive.

D. Contamination Of SDC

SDC was contaminated on three occasions when divers were working on well beads that were leaking gas. Some of the gas bubbles found their way into the trunk of the SDC.

Conclusion

There are two Westinghouse Cachalot systems, designated Cachalot 450 and Cachalot 850. The numbers 450 and 850 refer to the maximum diving depth planned for the system, although the 450 is capable of putting divers down to 600 ft.

Westinghouse (Sanford Marine Services) also has a system operating off Norway, which allows divers to work deep (400 ft) for short periods (30–60 min) and decompress inside a chamber. Additional saturation systems and manned undersea habitats are on the drawing board and will be fabricated as the market develops.

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