Operational Considerations for Wet Life-Support Equipment from Submerged Facilities

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Divers operating out of bases in deep water face conditions that are in many ways different from those familiar to surface-based divers. Although many of the hazards encountered are well known, others are new or greatly increased. The correct design and operation of the diver's personal life-support equipment are vital for safe and efficient operations. Personal equipment serves primarily to control the environment in the immediate vicinity of the diver's body. Certain factors, such as the partial pressures of gases, temperature, and gas contaminants, must be kept within limits, or dangerous consequences result. Others, such as general comfort and the ability to communicate, will affect the efficiency of the diver and thus have a direct bearing on safety. A number of different approaches have recently been taken in the development of personal life-support equipment. They include various combinations of breathing systems, head gear, and exposure suits. The ultimate intentions of all are to allow the diver to work efficiently and safely. Several systems are analyzed and compared with special attention to the solution of environmental and other hazards. Although many of the concepts are still experimental, there are some which give significant promise.

As diving operations have progressed into deeper water, divers have begun to operate from submerged bases. These bases are located on the ocean floor near the work site instead of on the deck of a surface support vessel. Three general types of submerged facilities have been developed. In most widespread use at present is the tetheredsubmer sible decompression chamber (SDC) or diving bell. A second concept is the mobile SDC or free-swimming lockout submersible. Both tethered and mobile SDC's are essentially elevators to take the divers to and from their work. Facilities for extended decompression and living quarters are usually provided through a mating capability to a topside deck decompression chamber (DDC). A third concept involves the use of living quarters actually installed on the bottom, which may be completely independent from surface facilities.

Divers operating from submerged bases are freed from many of the hazards and constraints of surface-based divers. A safe haven is provided in close proximity to their work. They do not have many hundreds of feet of hose strung out in the current between them and the surface. Decompression can be controlled precisely throughout its entire course. It is carried out in a pressurized SDC and in comfortable DDC facilities on the surface. In short, the diver is no longer separated from a livable environment by great depths of water and many hours of time.

Until the advent of submerged bases, most deep diving was done with standard helmet equipment (heavy gear). Heavy gear has a number of significant advantages. It has been in use for many years, and divers are thoroughly familiar with its operation. They are aware of its hazards and idiosyncrasies, and understand the precautions that must be taken. It can keep a diver relatively warm and dry and is comfortable for long exposures. Modifications for mixed-gas use do not alter the basic configuration of the equipment. Hence, experienced heavy-gear air divers do not usually have difficulty transferring to mixed gas. Communications are optimal since the diver's mouth and ears are in the same large air cavity. There is a sufficient volume of air or gas in the helmet and suit to allow the diver several minutes of conscious activity if his surface supply fails. Heavy gear has one major drawback. It is too large and cumbersome to be utilized efficiently from the confined space of most submerged installations.

Diver personal equipment serves primarily to control the environment in the immediate vicinity of the diver's body. Certain factors, such as partial pressures of gases, temperature, and gas contaminants must be kept within limits, or dangerous consequences result. Others, such as general comfort and the ability to communicate, will affect the efficiency of the diver and thus also have a direct bearing on safety. The gear also can provide greater or lesser protection from various mechanical hazards.

The control of the partial pressures of gases is the most critical function of deep water diving equipment. A man's metabolism requires a supply of oxygen and the elimination of CO_2. If the partial pressure of oxygen (PO_2) is too low, he will become unconscious with little warning. If it is too high, he is apt to go into convulsions with equally little warning. If the partial pressure of carbon dioxide (PCO_2) is too high, a number of symptoms result which may lead to unconsciousness. Too great a concentration of CO_2 also appears to hasten the onset of difficulties caused by high oxygen concentrations and inert gas narcosis. PO_2 is also inversely related to the partial pressure of inert gases in a breathing mix and has a direct bearing on decompression tables.

Temperature control is usually a matter of keeping the diver warm. A man who is cold is not only uncomfortable but is less efficient and less alert to potential hazards. In addition, cold tissue saturates and desaturates inert gas in a different manner from tissue at normal temperatures. The problem of cold must be considered, not only while the diver is in the water, but also after he has returned to his submerged base. It may not be possible to heat the base or to change apparel immediately after the wet portion of the dive.

Good communication between the diver, the submerged base, and supporting facilities is extremely important. When communications are marginal or absent, supporting personnel are greatly hampered in detecting hazards to the diver and in

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taking measures to alleviate those hazards of which they may be already aware. The communications problem is compounded by the great distortion of speech in the gas mixtures commonly used in deep water. Since the diver's voice is already difficult to understand, every possible measure must be taken to prevent further degradation by the gear he is wearing.

Many different approaches have been taken towards the development of personal life-support equipment for use from the new submerged facilities. A number of the more significant ones are outlined below. They include various combinations of breathing systems, head gear, and thermal protection suits. The ultimate intention of each system is to allow the diver to work as efficiently and safely as possible under the new conditions encountered.

Diving equipment in use today may be broken down into two broad categories. These are hose-supplied gear, where the breathing media comes to the diver from the submerged base or the surface, and self-contained gear where all of the breathing media is carried by the diver himself. The self-contained diver is often considered to have advantages deriving from the absence of a restraining umbilical cord. In shallow water the umbilical cord may be readily eliminated without seriously affecting the safety of the diver. On operations from submerged bases, however, the situation is radically changed. The diver has only one safe haven—the base. If he gets into trouble or gets lost, he can no longer retreat to the surface. To do so would almost certainly induce a fatal case of the bends. The umbilical cord has become a vital life line which leads to the only safety. A life line could, of course, simply consist of a length of rope. But if a man is going to put up with the inconvenience of a rope, it is little more inconvenient to put up with a hose and eliminate the need for packing cylinders of gas. Hence, for submerged base divers, self-contained gear loses most of its advantages.

Some early attempts were made to utilize open-circuit demand breathing systems in deep water. The equipment was available, and it was felt the system would supply a guaranteed, safe, premixed gas at a temporarily acceptable expense. Demand equipment functions satisfactorily as long as the diver is not exerting himself. The author has personally used such equipment in the ocean to depths of 440 ft without difficulty. As soon as divers began to work hard, however, problems developed. Effort known as breathing resistance is required to pull gas through a demand regulator. As the gas becomes denser with greater depth, the effort increases. Breathing resistance results in a higher alveolar PCO_2, which in turn leads to a higher PCO_2 in the bloodstream. Symptoms of excessive CO_2 rapidly become apparent in the forms of dizziness, headaches, and general malaise.

CO_2 problems have been particularly bad with demand systems where a full face mask or an open helmet has been used instead of a mouthpiece. The mask and helmet approaches were tried in order to rectify the communications difficulties introduced by a mouthpiece. However, this very greatly increased the dead air space in the breathing cycle. In addition, breathing resistance tended to be still higher than with mouthpiece systems. Even without a mouthpiece, communications with demand systems leave much to be desired. The noise of the regulator is such that it is difficult for the diver to hear the tender while he is inhaling. There is a strong tendency for a man to talk and then to hold his breath while listening to the answer. The effect on CO_2 retention can well be imagined.

Faced with severe difficulties using demand equipment, some diving operations resorted to a free-flow, open-circuit concept. Free flow was generally utilized with a full face mask or a small helmet. When adequate gas was flushed through the breathing spaces, problems with CO_2 and communications were eliminated. The expenditure of gas, however, became extraordinarily great. The amount of CO_2 inhaled must be kept below about 1% surface equivalent and preferably below $\frac{1}{2}$%. To achieve less than 1% requires a supply of 300 liters per min multiplied by the number of atmospheres absolute at the depth of the dive. To achieve $\frac{1}{2}$% requires exactly double this amount of gas. The gas cost becomes prohibitive for sustained operations.

A significant danger often develops with free-flow, mixed-gas, open-circuit diving. Management is, of course, interested in expending as little gas as possible. The diver obliges by reducing the ventilation in his breathing system to the minimum he thinks he can tolerate. The hazard derives from the fact that most divers can breath in excess of 2% surface equivalent carbon dioxide without being immediately aware of trouble. For some individuals the percentage is considerably higher. Divers reducing ventilation to conserve gas sometimes find themselves in severe difficulties before being aware of it.

A man uses only a small fraction of the oxygen in any single breath. Gas economy, then, requires that a breathing mixture be recycled to allow more efficient utilization of oxygen. The metabolic CO_2, however, builds up rapidly unless some means is employed to remove it. Normally this is accomplished by passing the breathing mixture through a canister of chemical absorbent at some phase of the cycle. When makeup oxygen is supplied as part of a mixture with inert gases, the system is known as a semiclosed circuit. When the makeup gas is 100% oxygen, the system is closed circuit. Present semiclosed-circuit recycling concepts differ primarily in the power source used to force the mix through the absorbent canister.

The U.S. Navy first attacked the recycling problem by installing a venturi system in a modified Mark-V diving helmet. A fresh supply of breathing gas from a small jet nozzle rushes through the venturi. Expired gas is sucked from within the interior of the helmet through the venturi tube and thence is forced through an absorbent canister and back into the helmet. Excess gas is released to the sea through an exhaust valve. Gas consumption is about 20% of free-flow, open-circuit ventilation.

In recent years, the Navy venturi system has been further modified to fit small compact civilian heavy gear. Such gear is still too large for efficient use from submerged facilities. The venturi principle has also been incorporated into at least one small form-fitting helmet now on the market. In order to reduce weight and bulk on the helmet, the venturi and canister have in this case been designed into a separate package that rides on the diver's back.

The fresh gas supply for venturi systems is always maintained at a constant pressure in excess of ambient pressure at the diver. The absolute volume of gas supplied at any given depth is constant. If the diver works hard, more oxygen is utilized, and more CO_2 is expired. Since recirculation is constant, the partial pressure of CO_2 in the helmet will go up. As most venturi systems are not designed to accommodate the maximum level of work that a diver may undertake, it is necessary for the diver working hard to remember to give his helmet additional ventilation through a bypass valve. The author has observed several instances where difficulties arose when such precautions were not taken. Usually, the results were the standard symptoms of excessive CO_2: dizziness, headaches, and a feeling of being unwell. In one case, a diver reported a near convulsion.

Properly used, a venturi breathing system produces very good results. The diver's face is free of all encumbrances. Communications and comfort are at a maximum, and breathing resistance at a minimum. Although far more economical than free-flow systems, it does not provide the economy of gas consumption which may be desirable. A venturi system would perhaps be the ultimate in breathing gear if adequate ventilation could be driven by the amount of new premixed gas, which will just supply the diver's oxygen needs. Unfortunately no way has yet been found to design a venturi with such efficiency. Much more gas is needed to power recirculation than to supply the diver with oxygen.

The problem can be circumvented by adding the minimum necessary amount of premix and devising some power source other than a venturi to effect recirculation. One way to accomplish this is to use the diver's lungs as a power source. The diver inhales directly from a breathing bag. He forces his exhalation through a CO_2 absorbent canister and back into the breathing bag. A constant supply of premixed gas containing makeup oxygen is metered into the breathing bag from either an umbilical hose or cylinders. Excess gas is exhausted to the sea. A pair of check valves keeps the gas cycling correctly. If the canister is properly designed, no significant CO_2 concentration can build up in the breathing bag. The effort of driving the cycle with lung power, however, can cause an increase of CO_2 tension in the diver's body. Lung-powered, semiclosed circuit apparatus has been in field use with the Navy and commercial concerns for several years. It has been used in deep water successfully. It is, of course, unavoidably burdened with breathing resistance and with the problems of mouthpieces or oral nasal masks.

The breathing resistance and mouthpiece difficulties may be eliminated by driving recirculation with an electrical blower instead of the diver's lungs. Apparatus utilizing a blower will normally incorporate a small form-fitting helmet. A breathing reservoir must also be provided, either in the form of a dry suit interconnected with the helmet or with a breathing bag. The diver inhales directly from the helmet. He need not have a mouthpiece, mask, nor other facial encumbrances. The blower circulates gas from the helmet through an absorbent canister and back through the helmet. Flow rates must be sufficient to insure that CO_2 levels do not rise above acceptable limits. Makeup gas is added at some point in the circuit.

The critical link in any semiclosed circuit apparatus not driven by a venturi is the addition of makeup gas. A number of accidents have occurred when the metering jet became obstructed and insufficient oxygen entered the system to replace that which was being metabolized. The partial pressure of oxygen in the breathing mix decreased until the diver became unconscious. In such a situation there is little if any warning. Normally, a man's body will tell him when he is out of breath. The warning is triggered by an excess of CO_2 rather than by a deficiency of oxygen. In a semiclosed circuit apparatus the CO_2 is, of course, removed. A venturi-powered system is fail-safe with respect to oxygen deficiency as long as the venturi is operating. It is quite obvious to the diver when it stops. The metering jet in a non-venturi system passes a relatively small amount of gas. The diver will probably not notice if the system has ceased to operate properly. Adequate safety with non-Venturi, semiclosed circuit systems will require a reliable warning device for malfunction of the metering jet. It will be highly desirable, in addition, to be able to monitor the PO_2 of the diver's breathing mix from the base and/or on the surface. Monitoring will not only help prevent accidents but will safely allow closer control of gas mixtures for more efficient decompression procedures and greater economy.

Ultimate efficiency in the conservation of breathing gas may be obtained by utilizing a fully closed circuit system. Enough pure oxygen is added to the circuit to just replenish that utilized by the diver's metabolism. Inert gas is added only when necessary to replace what is absorbed by the diver's body or lost through leakage. Closed-circuit units may be powered by the diver's lungs or with a blower unit. If a blower is used, the cycle may be confined to the diver, or it may include the submerged base.

Closed-circuit systems employing lung power have the same problems with breathing resistance and facial encumbrances as other demand systems. In addition, systems where the breathing cycle is confined to the diver embody not only the hazards of anoxia, but also of hyperoxia or oxygen toxicity. A failure in the control of oxygen or inert gases in either a positive or a negative direction will lead to critical difficulties with little warning. It is essential that adequate warning and monitoring devices are incorporated.

Some closed-circuit systems actually include the submerged base in the breathing gas cycle. In such systems the blower, more adequately described as a compressor-depressor, pumps gas from the base down to the diver and pulls his exhaust back to the base for purification. Two hoses are required. Systems presently in use employ two breathing bags, one for fresh gas and one for exhaust. Regulators maintain the correct volume of gas in each bag. Inhalation utilizes a demand regulator; hence, facial encumbrances and some breathing resistance are present. The diver does not, however, have to force his exhalation through the absorbent canister. It would be relatively simple to substitute a free-flow cycle of gas through the system for the present demand concept. Breathing resistance and facial encumbrances would be eliminated.

When the submerged base is incorporated into the diver's breathing cycle, the volume of gas involved is vastly increased. Several hours would ordinarily be required to deplete the oxygen in the base. Accordingly, requirements for monitoring PO_2 are much less critical. The greatest disadvantage of the system is that power requirements to cycle gas from the base to the diver and back against a pressure gradient are much larger than for a cycling system confined to the diver. Mechanical noise from the compressor-depressor can also be a significant problem.

All mechanical systems can fail. In the event of a personal gear failure, the diver must return as quickly as possible to his submerged base. The distance will normally not be great, but he may have to clear himself and his umbilical from the work. In some instances it may be quite important to spend a short period of time securing the work itself prior to departure. All of this indicates the need for an emergency supply of breathing gas. Such a supply can be carried in a small cylinder on the diver's back, or it can be taken from the umbilical hose through a valve bypassing the regular breathing cycle. The cylinder is somewhat more fail-safe, but the bypass will provide more gas. Whatever system is used, the emergency gas supply in the event of trouble, will provide the difference between an orderly retirement and a panic.

Thermal protection in deep water has a major bearing on a diver's comfort and on his ability to function. Temperature problems are aggravated by the high conductivity of the helium breathing mixtures normally used. When protection is by insulation alone, failure is a noncritical hazard. Even with complete flooding in the coldest water, there is adequate time for the diver to retreat to a submerged base. Thereafter one must, of course, take measures to decompress safely and avoid extreme hardship.

In a helium environment, insulation alone often will not suffice and supplementary heating becomes necessary. Heat may be provided by electrical resistance, circulated warm water, or circulated warm gas. Several potential hazards arise which must be guarded against in design. A short circuit caused by flooding or a broken wire in an electrical system can cause shock, burns, and even in some circumstances, fire. Loss of heat control in water or gas circulation systems can cause burns to the diver.

Consideration should be given to temperature control while the diver is in the base as well as in the water. Significant periods of time may elapse while the diver is in the base en route to or returning from his job. Normal body temperature is important from a physiological standpoint during the first stages of decompression. Any adjustable closed-circuit heating system, whether electric, water, or gas, should handle this problem adequately. Open-circuit systems, such as those in which expended warm water is dumped to the sea, may not be satisfactory.

When dry-type suits are used, attention must always be given to the problem of blowup (over-inflation of the suit with resultant loss of buoyancy control). This has long been a serious concern of conventional heavy gear divers but is sometimes forgotten with the introduction of new equipment. It would, needless to say, be embarrassing to be trapped in a suit full of gas suspended on an umbilical 100 ft above one's base.

The field of diving from submerged bases is as yet young. A relatively small amount of experience has been accumulated. It is too early to be able to say that one concept of life-support equipment is superior and another is unsatisfactory. Much more research, development, and field trial is needed. Each concept and procedure must be analyzed by the diving team with reference to situations existing at the time and place of the dive. Safety in the developmental phase can be enhanced if three basic guidelines are followed:

1) Each member of the crew is competent in his job and has a thorough working knowledge of the equipment being used.

2) The equipment is, within the limits of the state-of-the-art, conceptually and mechanically sound.

3) Means are included in the wet life support-system which warn the diver and supporting crew of hazards before they reach a critical level. An example would be the monitoring of oxygen partial pressures, which in themselves give little warning of dangerous variations prior to the onset of unconsciousness.

Almost all existing government standards and regulations, with respect to diving, apply to shallow water situations. Those which relate to operational procedures are usually inappropriate to commercial operations. Often they have been conceived and written by persons oriented to military or amateur diving who are unacquainted with commercial problems and procedures. In general, they are loosely, if at all, enforced, and serve primarily as a weapon to condemn a violator after an accident has occurred.

What can be done in the future to establish guidelines which will be workable and will effectively enhance the safety of deep water diving? The mere publication of a list of rules is unlikely to solve many problems. A significant question exists as to whether the industry is yet sufficiently stabilized to allow the establishment of intelligent guidelines. However, there are two areas where worthwhile results might be achieved. Most important is the establishment of adequate training programs for divers and supporting personnel. The author is convinced that efforts in this direction will be far more productive than fixed regulations. No amount of regulation can compensate for ignorant or foolish actions. Licensing of divers and other personnel according to grades of capability might be considered. The second area lies in the certification of equipment sold on the open market. Although the safe use of equipment is the responsibility of the diver himself, he has the right to expect that gear acquired on the open market is as safe and well built as we know how to make it. The establishment of a competent certifying authority would do much to provide this.

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Performance of Waterjet Propulsion Systems—A Review of the State-of-the-Art

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Waterjets may solve some problems facing high-speed marine propulsion. To judge their potential, a literature study was conducted to determine the state-of-the-art of waterjet technology with emphasis on 1) performance criteria and data, and 2) performance evaluation and experimental techniques. A general lack of definitive experimental data was noted, with the greatest need for information on the design of efficient, cavitation-free, high-speed inlets. Work also is needed on lightweight pumps capable of sustained high performance under relatively severe cavitation. Thrust efficiency was usually confused with propulsive efficiency, the product of thrust efficiency and the hull/waterjet interaction efficiency, which is a more definitive parameter but inherently more difficult to obtain. Model experiments are required to separate resistance and propulsive forces in determining this efficiency. A review of model experimental techniques and facilities shows the capability for carrying out the necessary experiments.

Nomenclature

C_p = $(p - p_o)/\frac{1}{2}\rho V^2$
d = diameter, L
e = mean roughness height, L
E = Euler number, $V/(\rho/2\Delta p)^{1/2}$
F_n = Froude number, $V/(lg)^{1/2}$
g = gravitational acceleration, ft/sec^2, L/T^2
H = pump head rise, ft, L
H_e = exit nozzle head, ft, L
H_i = inlet head, ft, L
H_1 = absolute pressure at shaft centerline—vapor pressure, ft, L
H_L = system head loss
H_{sv} = net positive suction head *npsh*, ft, L
H_s = static head, atmospheric + depth, L
J = advance ratio, V/Nd
K_H = head rise coefficient, gH/N^2d^2
K_L = system loss coefficient, $H_L/V_J{}^2/2g$
K_q = torque coefficient, $q/N^2d^5\rho$
K_t = thrust coefficient, $T/N^2d^4\rho$
k = jet velocity ratio, V_j/V
m = inlet velocity ratio, V_j/V_i
l = length, ft, L
l_s = ship length and model length, respectively, ft, L
M = Mach number, $(\rho V^2/E)^{1/2}$
N = rmp or rps, $1/T$
N_s = pump specific speed, $NQ^{1/2}/(gH)^{3/4}$
OPC = P_E/P_B
p = static pressure, lb/ft^2, M/LT^2
P_E = effective horsepower $(R \times V/550)$, ft-lb/sec, ML^2/T^3
P_B = brake horsepower $(2\pi Nq_{\text{brake}}/550)$, ft-lb/sec, ML^2/T^3
P_D = propeller horsepower (delivered), ML^2/T^3

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