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13 OPERATION AND TESTING OF MARK 10 MOD 3 UNDERWATER BREATHING APPARATUS

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INTRODUCTION

The deep ocean is the most difficult environment in which man has chosen to work. Life support equipment used in the deep ocean must be of the finest design because the ocean and the physical laws governing diving are unforgiving.

Closed-circuit apparatus for deep diving are highly desirable because of the breathing gas economics that can be effected. Helium gas, used in deep diving to eliminate the inert gas narcosis problem, is expensive and is a logistic problem because of the great amounts required if open-circuit or semiclosed circuit breathing apparatus are used. Gas consumption in open- and semiclosed-circuit apparatus increases with depth so that the gas consumption of a diver at 1000 ft is about 30 times as great as on the surface.

The Mark 10 Mod 3 is a closed-circuit, mixed gas underwater breathing apparatus designed for use from the surface to 1500 ft and to provide a minimum duration of 4 hours under any sea conditions. The Mark 10 Mod 3 (fig. 13.1) is a completely self-contained unit weighing about 62 lb in air. The apparatus senses oxygen partial pressure in the breathing gas mix and controls oxygen content of the breathing gas within narrow limits about a preset value.

It is this ability to sense and control oxygen partial pressure in an atmosphere that may contain less than 1 percent oxygen in a total pressure of 30 atm that is difficult to obtain but absolutely mandatory in closed-circuit, mixed gas underwater breathing apparatus.

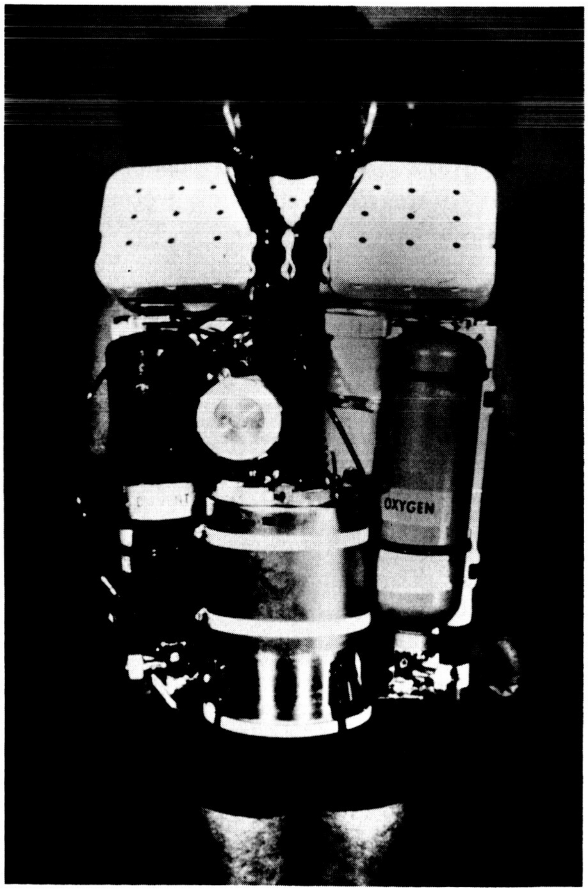

Figure 13.1 *Mark 10 Mod 3 breathing apparatus.*

SUBSYSTEMS OPERATION

Figure 13.2 is an overall schematic of the Mark 10 Mod 3. While the Mark 10 is and operates as a total system, it is composed of three subsystems:

1. The gas supply subsystem
2. The oxygen partial pressure control subsystem
3. The breathing circuit subsystem

Each of the subsystems will be discussed separately.

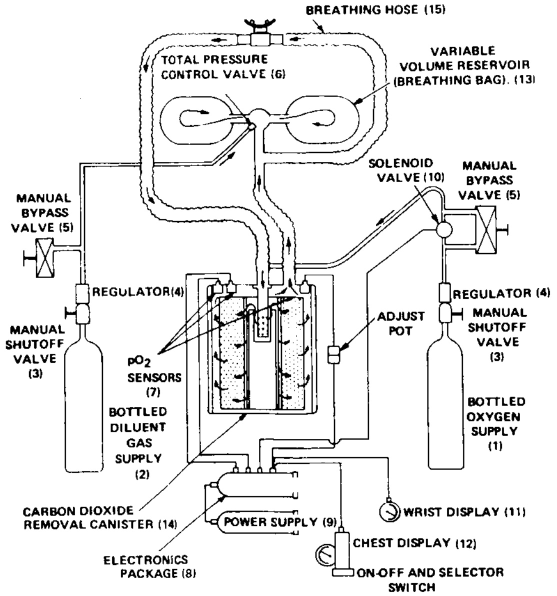

Figure 13.2 *Overall schematic of system.*

Gas Supply

The purpose of the gas supply subsystem is to store oxygen and diluent gases and introduce them, when required, into the breathing circuit in a controlled manner.

Oxygen and diluent gases are stored in individual 150 cu in. steel cylinders with a working pressure of 3000 psi (1) and (2). A manually operated shutoff valve (3) is attached to the cylinder. A constant differential pressure regulator (4) referenced to ambient pressure is attached to the shutoff valve by a yoke. This regulator is nothing more than a first stage regulator found in ordinary scuba equipment. Manually operated, spring-loaded bypass valves (5) downstream of the regulator provide an auxiliary method of adding diluent gas and oxygen.

Pressure Control

The total pressure control system (6) contains diluent add and gas vent valves that act to maintain breathing gas present in the breathing circuit in equilibrium with environmental water pressure. Threshold limits of 4 in. of water or gas pressure below ambient and 6 in. of water or gas pressure above ambient are established for diluent addition and venting.

The purpose of the oxygen partial pressure control subsystem is to ensure that the breathing gas delivered to the diver contains a constant predetermined partial pressure of oxygen regardless of depth.

Three oxygen partial pressure sensors (7) are located in the plenum on the outlet (inhalation) side of the carbon dioxide removal canister. The sensors are galvanic cells that generate a voltage proportional to the oxygen partial pressure in the gas at the sensor face. Each sensor is completely independent of the others so that there is redundant measurement of the oxygen partial pressure. The output of two of the three sensors is fed to the electronics package (8), where it is used to control oxygen partial pressure in the gas supplied to the diver. The output from the third sensor bypasses the electronics package and goes directly to the wrist and chest displays (11) and (12).

The signals from the sensors, which are fed to the electronics module, are amplified and compared to a preset reference voltage corresponding to the desired oxygen partial pressure. If the highest sensor output is less than the reference, voltage power is applied to the solenoid valve (10).

The valve opens and admits oxygen to the breathing circuit for 0.5 sec. If the highest amplified input is higher or equivalent to the reference voltage, the solenoid valve does not open and oxygen partial pressure is decreased through metabolic consumption. The sensors sample the breathing gas every 5 sec.

The reference voltage is set prior to each dive. The system can accept two reference voltages. This enables the apparatus to provide a low oxygen partial pressure for normal diving operations and to provide a high oxygen partial pressure when accelerated decompression is desired. The low oxygen partial pressure set point can be varied between 0.20 and 1.0 atm. The range of the high oxygen set point is from 0.95 to 1.25 atm. Adjustment of the set points is accomplished by adjustment of two potentiometers in the electronics module.

Power to operate the electronic components comes from 20 rechargeable nickel cadium batteries housed in a separate module (9). They are charged with a special battery charger provided with the apparatus. The battery module may be removed for charging or charging may be accomplished with the module attached to the structural frame. Provision is made for normal charge, trickle charge, and automatic switchdown from normal to trickle charge so the charger may be connected for an indefinite period without danger of overcharging.

The wrist display (11) is connected to the third oxygen partial pressure sensor through a calibration trim pot. The wrist meter provides an independent indication of the oxygen partial pressure in the inhalation side of the breathing circuit, thus providing a basis for manual control of the apparatus should the automatic control system fail. The meter face is marked to indicate the two ranges of oxygen partial pressure control. Two lamps in the wrist display are responsive to the alarm circuitry contained in the electronics module. The alarm circuitry monitors three functions:

1. Sensor 1 output compared to the reference voltage
2. Sensor 2 output compared to the reference voltage
3. Battery voltage level

When all functions are within normal tolerances the amber lamp is lit. If the output of either control sensor is ±25 percent from the reference voltage or the battery voltage is below 22.5 V, the amber lamp is extinguished and the red lamp lit. The red lamp serves as a warning to the diver that an out-of-tolerance condition exists and corrective action must be taken.

The chest display (12) has two meters: one calibrated to read in atmospheres and one calibrated to read in volts dc. The tolerance band for normal operation is marked with luminous material as on the wrist display. A multiposition selector switch on the chest display provides for:

1. Turning power to the apparatus off (OFF).
2. Reading high and low oxygen partial pressure settings (low oxygen set, high oxygen set).
3. Reading battery voltage (low bat/high bat).
4. Selecting high or low oxygen partial pressure operation (low sen 1, low sen 2, high sen 1, high sen 2).
5. Reading the output of sensors 1 and 2 (low sen 1, low sen 2, high sen 1, high sen 2).

When the selector switch is in either the low sen 1 or low sen 2, the apparatus will control about the low oxygen partial pressure set point and the output of either sensor 1 or 2, whichever is set, will be displayed on the chest display. Similarly, when the selector switch is in the high sen 1 or high sen 2 positions the apparatus controls about the high set point and displays the output of the appropriate sensor on the chest display. Detents are provided so that the apparatus cannot be accidentally turned off or switched from one control range to another. Positions are provided so that battery voltage may be monitored while the apparatus is operating in either the high or low range.

The device on the left in figure 13.3 is the chest display. Note the two scales, luminous materials, and detents on the switching device. The switch is so constructed that a diver wearing bulky gloves or mittens can easily operate it. The wrist display is on the right. Notice the simplified scale and warning lights. The diver normally wears the wrist display on his left wrist and clips the chest display to a D ring provided for it on the right shoulder strap. The wrist display is out of the way but readily accessible to the diver.

Breathing Circuit

The breathing circuit subsystem provides respirable gas to the diver in sufficient quantity and removes carbon dioxide and moisture from the expired gas.

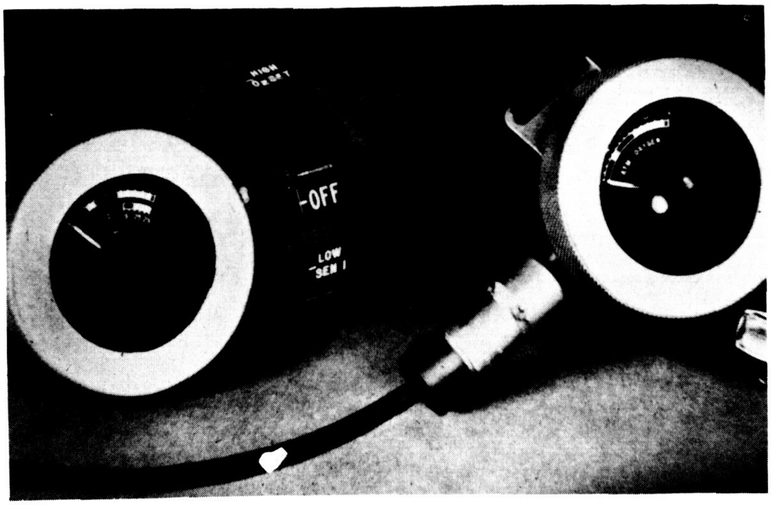

Figure 13.3 *Wrist displays.*

The variable volume reservoir (fig. 13.2 (13)) is composed of two neoprene bags and acts as an accumulator for the gas while it is outside the diver's lungs. The reservoir, which has a total volume of 6.25 liters, is located on the inhalation side of the circuit.

The carbon dioxide removal canister is located in the center of the backpack. The canister is of unique design for diving equipment in that it is radial flow and is provided in prepackaged units. Figure 13.4 shows the principal components. Expired gas enters the center of the canister, passes through a moisture absorber and into the outlet plenum. The three oxygen sensors and oxygen addition line are located in the plenum at the top of the chamber. The carbon dioxide absorbent cartridge forms an integral part of the canister assembly in that the bottom of the cartridge forms the bottom of the canister so with this arrangement it is not possible to dive with an empty canister. To reduce the possibility of diving with a used cartridge, a piece of soluable paper dissolves on water entry to reveal the word "used." All portions of the breathing circuit are connected by flexible neoprene hoses. Note that the breathing hose (15) fits down the center of the breathing bag box and lies very close to the diver's head. This is a comfort feature and reduces the possibility of the hose snagging.

Although the apparatus is shown with a mouthbit, it may be used with a variety of full facemasks (fig. 13.5). The normal use is a face-sealed full facemask with an oral-nasal insert, communications, and respiratory gas temperature monitoring.

Figure 13.6 shows integration of the three subsystems to form the complete breathing apparatus. Note that the subsystems are all interdependent.

While component testing and extensive unmanned systems testing are carried out in the development of deep diving life support systems, it is imperative that manned testing be done in a simulated deep ocean dive. Simulated environment testing allows careful monitoring of the divers and equipment that is not yet possible in the deep ocean and allows immediate assistance should trouble develop. Such equipment testing

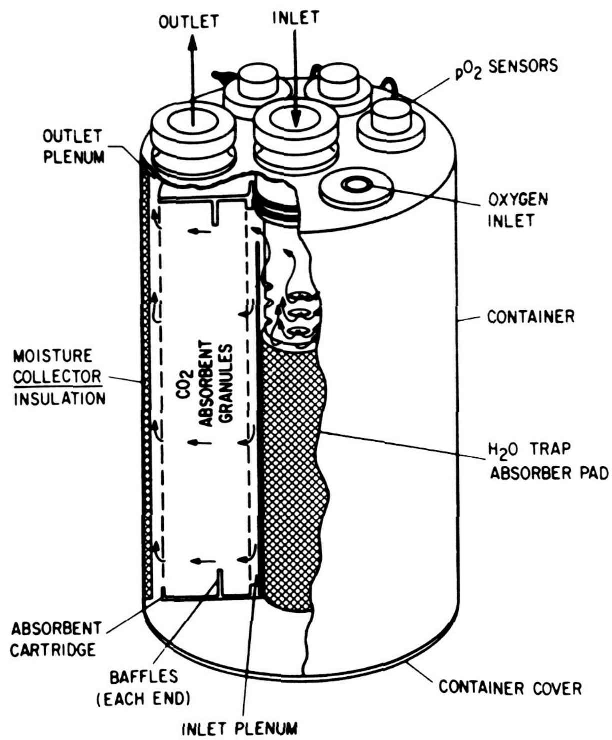

Figure 13.4 *Carbon dioxide removal canister.*

Figure 13.5 *Full-face mask.*

is generally done in two phases. The first is in warm (70° to 80° F) water and the second in cold (29° F) water, both at the simulated depth at which the expected use will occur. The warm water test verifies the basic function of the apparatus and establishes its ability to effectively serve as life support equipment. In the cold water testing, a condition simulating the extreme conditions that can be reached in the ocean is reached. The cold water imposes a stressful condition on the apparatus such as is likely to occur in actual service. While 29° F may not seem to be an extreme condition in conjunction with dense helium it imposes severe stresses on mechanical and electrical functions, and the carbon dioxide absorption process.

HYPERBARIC TESTING

Facilities for conducting such hyperbaric tests are rare and highly specialized. Figure 13.7 does not represent any particular facility or an ideal facility, but is a composite of features generally found. The hyperbaric facility is a complex of pressure chambers designed for living and testing at elevated pressures. At least one of the chambers can be filled with water. A dry chamber, generally known as an igloo, is provided directly above the wet chamber as a diver tender station and as additional living space. A living chamber and separate entrance lock are usually provided. Supply locks are provided so that equipment, medical supplies, food and the like may be passed into and out of the chamber.

Ancillary systems include:

1. An environmental control system to control temperature humidity and odor in the chambers as well as to remove carbon dioxide
2. A master control console and chamber atmospheric monitoring equipment
3. Closed circuit television with videotape capability
4. A water filtration system to provide clarity and biological purity
5. A water temperature control system
6. Appropriate test instrumentation
7. Gas storage and mixing facilities
8. A helium reclamation facility

Phase I Tests

The first test dive with the Mark 10 Mod 3 was in June 1970 at the Navy Experimental Diving Unit (EDU) in Washington. The dive profile was essentially as shown in figure 13.8. Compression was in 200-ft increments with three-day stops at each depth. Two days at each depth were spent in testing the apparatus while the third day was used for experiments in breathing cold gas at depth. The results of the cold gas studies had a significant effect on subsequent testing.

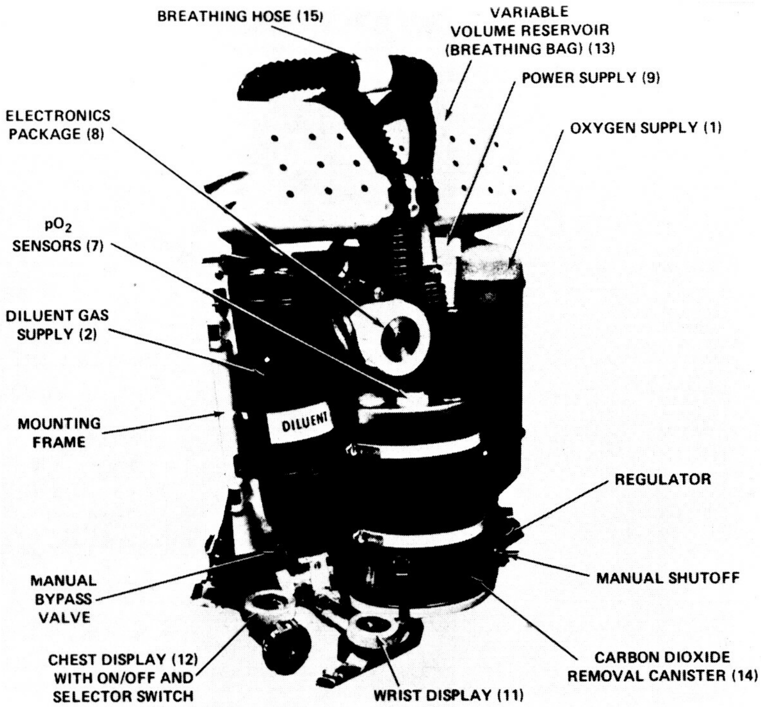

Figure 13.6 *Complete breathing apparatus.*

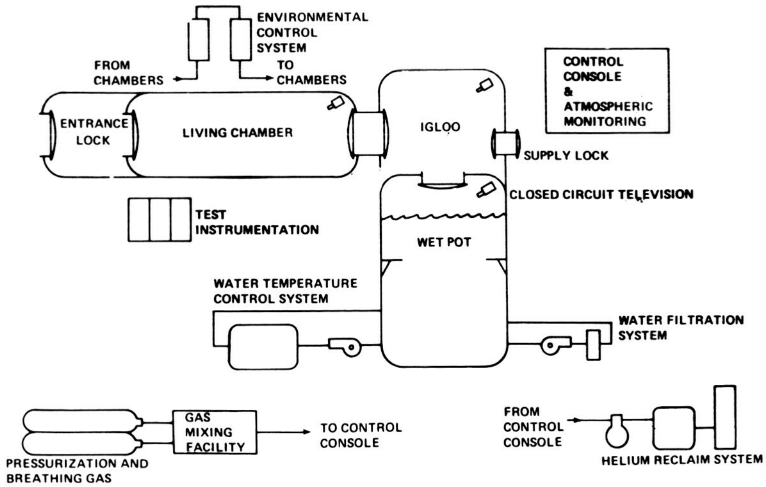

Figure 13.7 *Typical hyperbaric test facility.*

The primary areas of interest in this test were:

1. The ability of the apparatus to effectively control oxygen partial pressure and to provide the diver with an adequate amount of breathing gas while working at a known work rate under controlled conditions
2. The duration of self-contained gas supply at various depths between 200 and 1000 ft
3. The duration of the carbon dioxide absorbent canister at various depths.
4. Reliability and maintainability of the apparatus

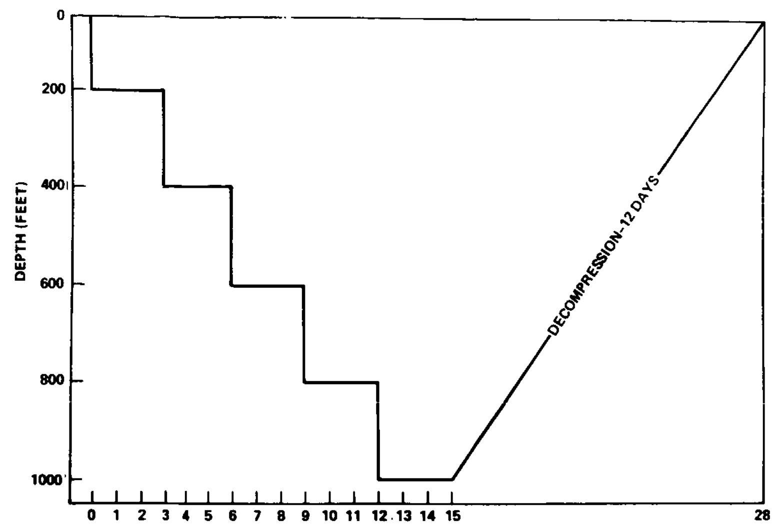

Figure 13.8 *Approximate dive profile of test at NEDU.*

In conducting these experiments the primary parameters to be measured are oxygen and carbon dioxide content in the inspired gas. To measure these a sample is drawn from the inhalation side of the breathing circuit and analyzed by instrumentation outside the chamber. In the chamber one diver swims against a counterbalanced trapeze weighted to represent a current of 0.8 knots, the other lifts a 70-lb weight to a height of 30 in. 10 times/min (10-min work periods alternate with 5-min rest periods).

The dive is terminated when the gas supply is exhausted or when the partial pressure or carbon dioxide level in the inspired gas reaches 3.8 mmHg or 0.5 percent, surface equivalent.

The dive at EDU was a success. Canister durations greatly exceeded expectations showing little or no effect from increased gas density at greater depths. Gas supply durations became longer as divers became used to the apparatus and stopped wasting diluent gas by unnecessary clearing of the face mask. In all cases where gas consumption was limiting, the limitation was exhaustion of diluent gas rather than oxygen. In some cases the divers were terminated prior to exhaustion of the gas supply or carbon dioxide absorbent because of diver fatigue or because the judgement of the diving officer indicated early termination was desirable. One anamoly that was discovered was that as depth increased the oxygen partial pressure variation that occurred when oxygen was added increased. This is understandable because the regulator outlet pressure was a constant amount above ambient, and oxygen addition was for a fixed period. As an example, at 1,000 ft with a nominal oxygen partial pressure of 0.40 atm the partial pressure would rise on addition of oxygen to between 0.60 and 0.70 atm. The variation was not physiologically dangerous but was greater than was desirable. As a result of the success of this dive the second phase of the testing was begun without major modification of the apparatus.

Phase II Tests

The second phase of the testing was carried out in the hyperbaric complex of Taylor Diving and Salvage Company in Belle Chase, Louisiana. Taylor was chosen because it has a large modern hyperbaric facility and a staff with unusual experience in experimental diving. The dive was to be in

200-ft increments to a depth of 1000 ft. During the period at 1000 ft an excursion was made to 1100 ft where the divers worked for 40 min and returned directly to the saturation depth. This was the deepest wet dive yet made in the United States.

Water temperature was maintained at 29° F throughout the dive. While the equipment parameters remained the same (i.e., gas consumption, carbon dioxide removal system performance, and oxygen partial pressure control system performance) much more extensive monitoring of the divers was required and considerable equipment was provided for thermal protection.

Thermal protection to the divers was provided by a hot water system integral to the hyperbaric facility. Hot water was supplied to each diver's open circuit suit at 110° F and a flow rate of 3 to 4 gal/min. A 0.125 in. thick closed-cell neoprene suit was worn under the free flooding suit as protection against burning should the hot water temperature momentarily become excessive.

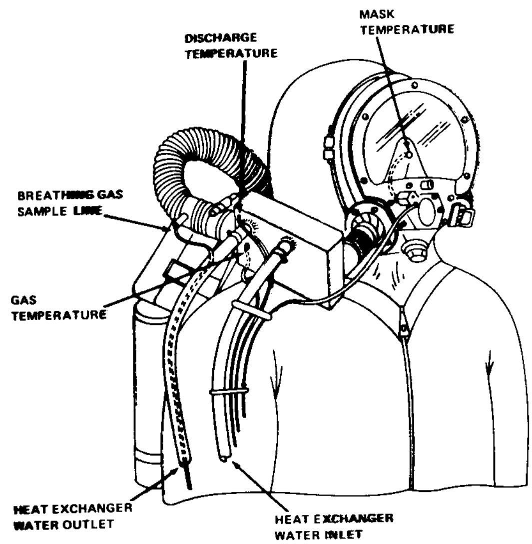

Figure 13.9 *Breathing gas sampling line and thermistor placements.*

The cold gas testing, mentioned previously as having been carried out at the EDU in conjunction with the first phase testing, showed that the diver's breathing gas must be heated in deep diving. If it is not heated, the heat loss through the diver's respiratory tract will be intolerable. To provide respiratory heating a heat exchanger was attached to the diver's mask (fig. 13.9). The heat exchanger was a hot water to gas heat exchanger supplied with hot water from the diver's breathing gas supply. The exchanger was intended as an engineering model only and not as an operational piece of equipment. It was successful in that it provided satisfactorily warm gas thereby making it possible to conduct the dive.

Continuous samples of diver breathing gas were drawn from the inhalation side of the circuit and for analysis outside the chamber for carbon dioxide and oxygen content. Both quantities were recorded on strip charts. Notice that the breathing gas sampling line passed through the gas heat exchanger outlet line. This was necessary to prevent condensation and freezing of the moisture in the sample line. Freezing could cause blockage of the line and make it necessary to abort the dive.

A temperature harness was provided for monitoring of significant temperatures (fig. 13.10). Six skin probes located as shown were provided in addition to a rectal probe and gas heater and mask temperature monitoring. The mask temperature was the only one that changed rapidly so it was the only one connected to a continuous recording device, the variation in mask temperature provided the diver's respiration rate.

The dive profile (figure 13.11) shows that essentially one day was spent at each depth with the time varied as necessary to accomplish the purposes of the dive. Problem areas that are worthy of discussion because they influenced the conduct of the evaluation showed up at various times.

The gas regulators provided with the apparatus were specially made of 90-10 copper-nickel. These regulators proved to have such an extremely high failure rate that their use was discontinued at the 200-ft dives and all regulators were replaced by conventional brass regulators. Upon replacement no more failures ocurred.

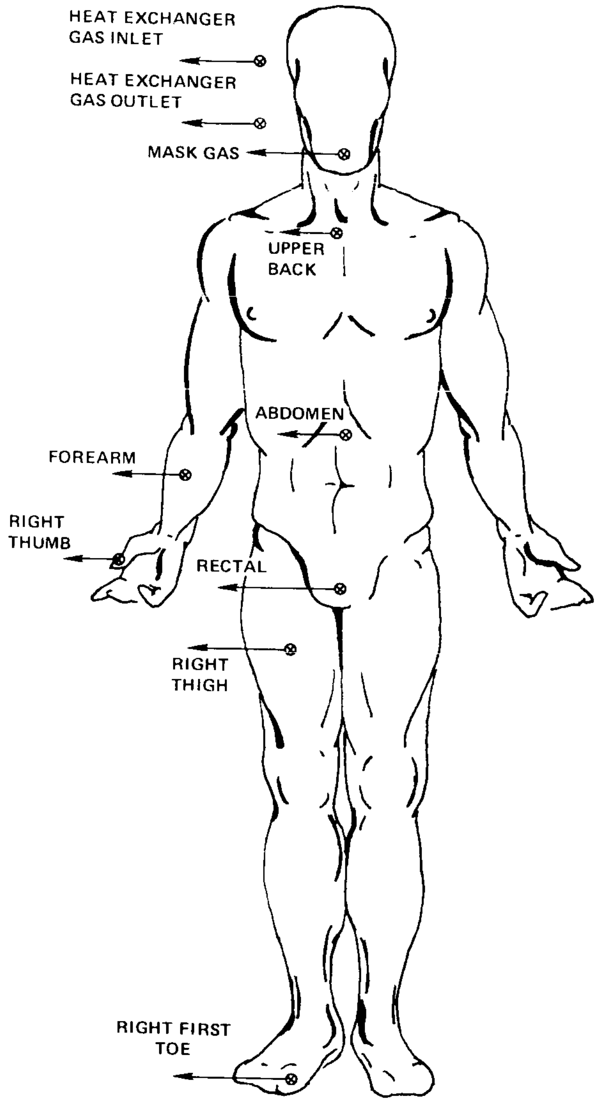

Figure 13.10 *Temperature monitoring of diver.*

The annoying and frustrating ability of helium to be absorbed by almost everything requires that equipment be decompressed in the same matter as people. Even though the equipment was decompressed slowly in accordance with a schedule that should have been extremely safe, the sensors and cables proved to be as unpredictable as the divers in reactions to decompression. Several sensors and cable assemblies suffered from the bends and had to be replaced. A number of electronics packages failed and had to be replaced.

Leakage into the mask was a problem during all dives. The original mask seals of open-cell neoprene foam were replaced by individually-fitted mask seals with a covering of closed-cell neoprene foam that were fabricated by General Electric. Face seals were slightly more effective after the replacement, but leakage into the mask continued to be a problem. Divers said that the torque of the heat exchanger attached to the mask tended to break the mask seal when turning the head. The adverse effect on evaluation of the apparatus from mask leaks derives from canister flooding resulting in decreased function time and increased diluent gas usage rate to purge the mask of brine. Gas cylinders were thus exhausted prematurely and had to be replaced.

Internal blockage of the heat exchanger core occurred as a result of the reaction of the calcium chloride brine with the aluminum core. The heat exchangers were clogged to the extent that only a trickle of water could be forced through them. Flushing with inhibited sulfamic acid solution cleared corrosion and reestablished water flow; however, one exchanger then leaked water into the gas breathing side and had to be replaced.

It was necessary to use calcium chloride brine to lower the freezing point of the wet pot liquid to 20° F, so that freeze-up of the heat exchanger would be avoided in cooling the wet pot liquid to 29° F. Although calcium chloride solution was less corrosive than sodium chloride solution, it caused severe irritation of the skin of the divers and extended small scratches and abrasions to weeping purulent ulcerations of the skin. Eye and ear canal irritation was a problem. These factors progressively affected more divers and prevented their further immersion in the wet pot in an effort to avoid worsening of their conditions. This problem adversely affected evaluation of the Ex 10-Mod 3, especially during the ascent phase when more of the scheduled time on the apparatus would have been accumulated. Warm fresh water showers, skin lotion, and ear canal hygiene with acid-alcohol drops were all to little avail in preventing the irritating effects of the brine on the diver's ears, eyes, and skin.

In spite of the problems encountered during the dive, sufficient data were gathered to make reliable statements about the performance of the apparatus and enough information was gathered to positively identify problem areas.

The oxygen partial pressure control was reliable and always within safe limits using the low oxygen partial pressure range. In the high range, oxygen partial pressures soon became higher than would be tolerable for long exposures.

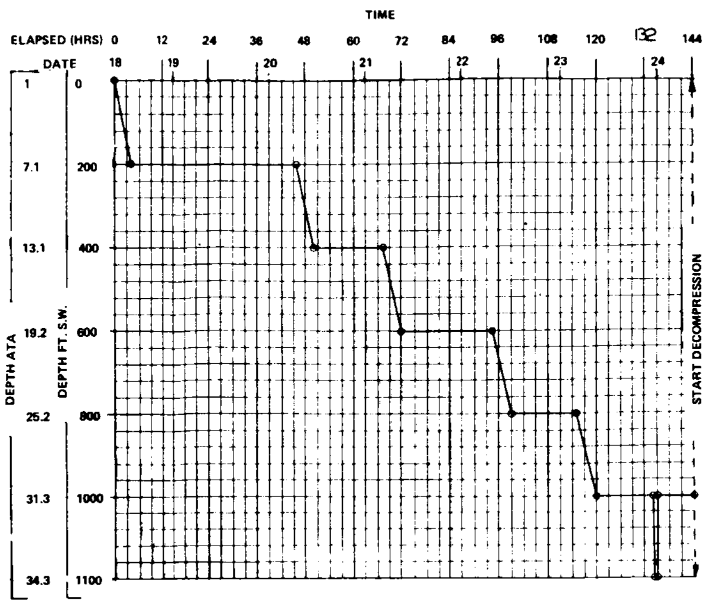

Figure 13.11 *Compression profile.*

Excursions of oxygen partial pressure about the set point had a total value that averaged between 0.15 and 0.20 atm as shown in figure 13.12, a typical strip chart. While this variation is within physiologically safe limits it is greater than desired. The apparatus is now being modified to reduce these excursions. Two basic changes are being made: sensor sampling will occur at 2-sec intervals with a 200-msec oxygen addition to reduce the mass of gas added at any one time, and oxygen

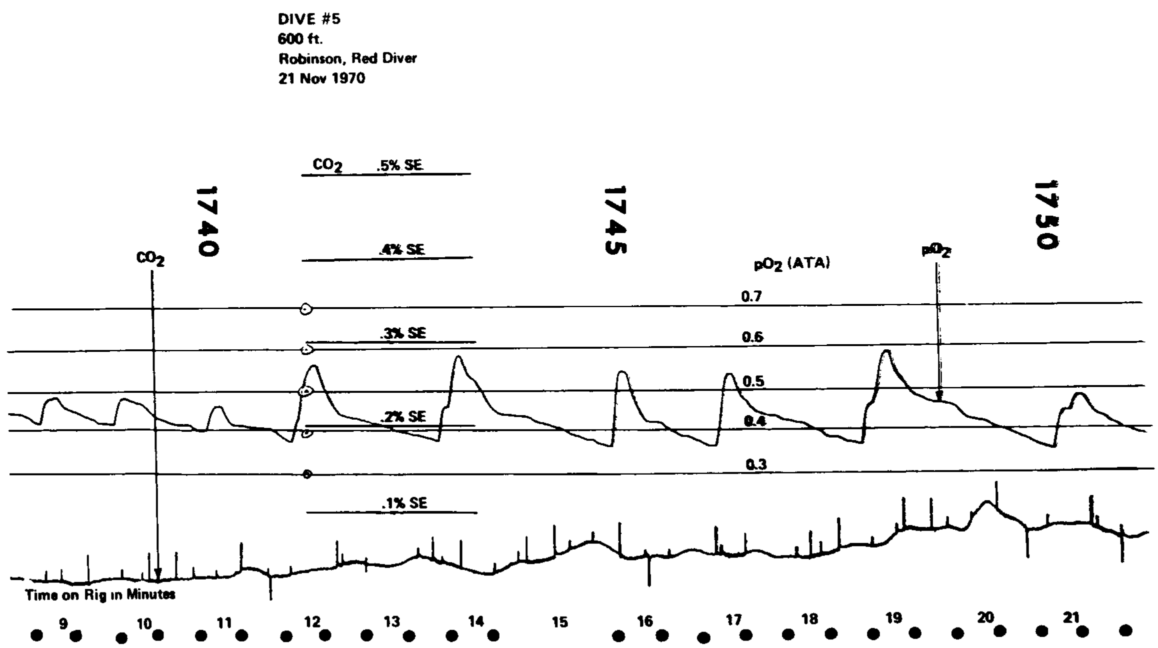

Figure 13.12 *Typical strip chart.*

addition will be divided between canister inlet and outlet to permit more thorough mixing before sampling.

The phenomena of set point drift remains unexplained but is believed to be related to the establishment of thermal equilibrium in the apparatus as it occurred within the first 15 min of the dive.

Carbon dioxide absorption performance was very disappointing. The predicted minimum durations are in all cases well below the desired 4-hr durations and well below the values obtained from the warm water dive at the EDU. The reduced canister performance can be attributed directly to the cold water and the cold dense gas that was being scrubbed. The heat capacity of a helium oxygen mixture at 30 atm is huge and the gas entering the canister was at ambient temperature. The carbon dioxide absorption reaction could not function effectively. Careful thought indicated that because of the radical flow through the canister, heating it with a water jacket as is usually done would not be satisfactory. A heat exchanger (fig. 13.13) was installed in the breathing gas circuit ahead of the canister with the exhaust water led down through a sheath covering the remaining hose and over the canister. This system was used on some swims during decompression. The results indicated an improvement in performance, but as swims during decompression were limited to 2 hr, the useful canister life was not determined. The installation of a complete heating system for the apparatus and for breathing gas systems is planned that will enclose the entire apparatus in a hot water filled bag with water flowing out through the double walled breathing hoses.

On the positive side, the self-contained gas supply proved adequate for working dives at all depths with predicted gas durations far in excess of expected diving times. Results are summarized in figure 13.14.

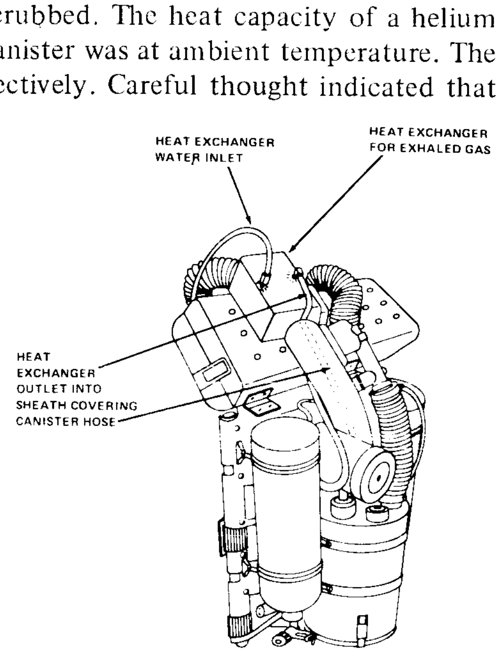

Figure 13.13 *Special canister heating system.*

CONCLUSIONS AND PROSPECTS

The total test results indicate that the Mark 10 Mod 3 apparatus has certain inadequacies but with modifications that are well within the engineering state-of-the-art can be used to support divers at low temperatures and great depths. A program is currently underway to make the necessary modifications. In the immediate future, another cold water test is planned for 1971 after the modifications have been made. A technical evaluation in the open sea will be conducted off Hawaii at 520 ft. If the results of these evaluations are satisfactory, an operational evaluation using the Mark 1 deep dive system will be conducted in the spring of 1972. This evaluation will be a series of open sea dives to 1000 ft. In addition to its use as a deep diving apparatus the Mark 10 has obvious application in clandestine operations. Its use in this area will be the subject of thorough investigations.

RESULTS OF COLD WATER TESTING
OXYGEN PARTIAL PRESSURE CONTROL

1. PHYSIOLOGICALLY ACCEPTABLE CONTROL OF OXYGEN PARTIAL PRESSURE
2. UNDESIRABLY GREAT VARIATIONS IN OXYGEN PARTIAL PRESSURE WITH OXYGEN ADDITION
3. UNDETERMINED BUT PHYSIOLOGICALLY SAFE VARIATION OF OXYGEN SET POINT

CARBON DIOXIDE ABSORPTION EFFECTIVENESS INSUFFICIENT

1. CANISTER DURATION

PREDICTED MINIMUM DURATIONS:

200–400 FSW	90 MINUTES
600 FSW	70 MINUTES
800–1000 FSW	45 MINUTES

GAS CONSUMPTION

1. ADEQUATE FOR WORKING DIVES AT ALL DEPTHS

	OXYGEN	HELIUM
GAS CONSUMPTION:	0.93 slpm	0.68 slpm
PREDICTED DURATION:	9.575 HRS	10.920 HRS

Figure 13.14 *Test results.*