



DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
PANAMA CITY, FLORIDA 32401

IN REPLY REFER TO:

EVALUATION OF THE CONSTANT PARTIAL
PRESSURE OXYGEN UNDERWATER BREATHING
APPARATUS.

Navy Experimental Diving Unit

Report No. 3-52

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OBJECT

The object of this test is to evaluate and determine the potentialities of the constant partial pressure self-contained oxygen underwater breathing apparatus (Marion Device) submitted by the Old Dominion Research and Development Corporation, Erion, Virginia. The tests have been conducted in such a manner that the following performance data could be recorded:

- (a) Analysis of gas, and fluctuation of analysis from the normal.
- (b) Reliability of the analyzer and of the control valve.
- (c) Endurance of the unit.
- (d) General comfort and performance of the underwater breathing apparatus.

DESCRIPTION OF THE UNIT

GENERAL

The apparatus utilized in this evaluation is the first experimental model of an underwater oxygen breathing apparatus which automatically controls the oxygen partial pressure at a pre-set value and maintains this constant oxygen partial pressure independent of depth.

The complete apparatus consists of separate oxygen and air cylinders, a carbon dioxide absorbent canister, an electronically controlled oxygen valve, an oxygen pressure regulator, an oxygen analyzer, and a battery pack. The above components are rigidly attached to an aluminum plate upon which a water tight cover containing the breathing diaphragm is attached by means of forty-eight (48) through screws. The control valves for both oxygen cylinder and air cylinder extend through the lower end of this cover and are made water tight by means of packing glands. A water tight sensor control switch is installed on the outside of the cover midway between the control valves. The mask breathing tube fittings extend through the back plate at the top and are made water tight by means of washers and packing nuts. Enclosure (1) is a photograph of the outer water tight cover. Enclosure (2), (3), and (4) are photographs showing the components parts of this apparatus.

The apparatus is designed for circular air flow. That is, the expired breathing medium leaves the face mask via a breathing tube to the absorbent canister, passes through the canister into the breathing bag (which is in this case the

space inside the apparatus cover), and returns to the face mask via a second breathing tube upon inspiration. The canister connection has a small sampling tube installed in such a manner that with each exhalation the sample chamber of the sensor unit receives a small sample of the expired breathing medium. Thus, the breathing medium is analyzed after each exhalation of the diver or swimmer.

Many of the component parts utilized in the apparatus were taken directly from other underwater breathing apparatus and were, therefore, not specifically designed for use with the present outfit. This is true of the absorbent canister, face mask, and breathing tubes, which were all taken from an old discarded Lambertsen outfit, and of the air and oxygen cylinders which are standard hospital type cylinders. A standard two stage Airco regulator was used to control the oxygen pressure to the electronic valve. From the information obtained as a result of this evaluation it should now be possible to design component parts which are more satisfactory for this specific apparatus and which provide for greatly improved performance.

OXYGEN CONTROL DEVICE

The use of a device mounted within a self-contained underwater breathing apparatus to effect automatic control of oxygen partial pressure at a constant pre-set value is an entirely new idea which is used in this experimental apparatus for the first time. Essentially the device consists of three components: (1) a sensor or oxygen analyzer, (2) an electronically operated oxygen valve, and (3) a battery pack to supply the required electrical power to the valve and sensor.

(1) Sensor (Oxygen Analyzer)

In order to control successfully the percentage of oxygen at a predetermined value in an air-oxygen system for use within a diving apparatus, it is necessary to utilize some physical or chemical property of the gases. In this instance the Old Dominion Research and Development Corporation has utilized the paramagnetic properties of oxygen successfully to maintain the partial pressure of oxygen at a constant pre-set value in the air-oxygen mixture. The control is accomplished in accordance with the following principles.

Since oxygen, by nature, is strongly paramagnetic (attracted into a magnetic field), the oxygen partial pressure of a gas sample within the system may be accurately determined by measuring the magnetic susceptibility of the gas sample with a magnetic torsion balance located within the sample cell (Beckman principle). The magnetic balance consists of a hollow glass needle test body, with a flag like extension which is cemented to a nylon filament (5 micron diameter) suspended within the test cell. The hollow needle test body is subjected to a magnetic force which is dependent upon the difference between the volume magnetic susceptibilities of the glass needle test body and of the gas which the test body displaces.

In the present sensor, whenever the susceptibility of gas changes as a result of changing composition or pressure, the test body rotates to an equilibrium position. In addition, as the test body rotates, the flag like extension of the test body interrupts the light rays from a 1.2 volt light bulb lens. This interruption of light actuates a photo-electric circuit connected to the oxygen valve, causing it to close when the oxygen partial pressure reaches the pre-set value. Since a new gas sample is directed into the test cell via a sample tube each time the diver exhales, continuous analysis of the diver's breathing medium is accomplished.

(2) Electronic control valve

The electronically operated oxygen valve utilized in this apparatus is automatically controlled by the sensor unit through the photo electric circuit described above. When the oxygen partial pressure within the apparatus is equal to or greater than the pre-set value of the sensor, the photo electric circuit becomes energized, activating the magnet of the oxygen valve. When the magnet is engaged, a contact arm is moved against the tension of a spring to cause a valve on this arm to close the valve orifice, preventing passage of oxygen through the valve. Deenergization of the valve magnet photo electric circuit when the oxygen partial pressure falls below the pre-set value permits the valve to open and to admit oxygen to the system. A conventional two stage reducing regulator installed just ahead of this valve regulates the oxygen pressure to the valve to give the desired flow through the valve orifice. Discharge of oxygen from the control valve is through a signal element in the form of a whistle. This whistle is clipped to the back plate of the apparatus so that the diver or swimmer may feel its vibrations underwater.

(3) Battery pack (final form)

The third component of the oxygen control device is the battery or power pack. This pack is made up of three different type batteries required to supply the correct voltages for proper operation of the various electrical components. The pack consists of: one 45-volt "B" battery (similar to a Burgess Model M30); two 30-volt "B" batteries (similar to Ever Ready Model 413E) connected in series, or four 30-volt "B" batteries (similar to Ever Ready Model 406E) connected in series-parallel; and eight 1 1/2-volt mercury "A" batteries (similar to Mallory Model RM-12) connected in parallel. After assembly, the batteries are inserted into a plastic container and the lead wires are connected to the proper components.

Other batteries may be used instead of those listed above provided they supply the three required voltages of 60, 45, and 1 1/2. However, during this evaluation many other types of batteries have been tried and it has been found that the above listed type are by far the most satisfactory tested.

DISCUSSION AND RESULTS

The first experimental model of the constant partial pressure oxygen underwater breathing apparatus was received for evaluation by the Navy Experimental Diving Unit on 23 July 1951. As received, the senser unit was calibrated for control of oxygen partial pressure at a value of .5 atmospheres or a 50% O₂ concentration at atmospheric pressure. The first trial dive was made the same day in the Navy Experimental Diving Unit wet tank to a depth of 33 feet. Oxygen concentration was measured continuously during this dive (and all other dives) by means of a Beckman oxygen analyzer mounted outside the tank. Continuous gas sampling was accomplished by means of a sample tube connection from the apparatus to the Beckman analyzer. The gas sample was drawn directly from the breathing bag of the apparatus and thus representative sampling was accomplished. The Beckman oxygen analyzer was periodically calibrated to insure an accuracy of results within 2 percent.

The oxygen concentrations recorded on this first dive indicated that the senser was operating satisfactorily in the calibration range. Analysis of the breathing medium at the surface gave results in the range of 48-54% oxygen. At 33 feet the oxygen concentration recorded was in the range of 24-28%. Thus, as received the apparatus was functioning satisfactorily in regard to the control of oxygen partial pressure. Upon completion of this trial dive the apparatus was turned over to the Navy Experimental Diving Unit for an evaluation of the apparatus.

PART I

EVALUATION OF THE OXYGEN CONTROL DEVICE (ORIGINAL MODEL)

The oxygen control device whereby automatic control of oxygen partial pressure at a constant value is accomplished within a self-contained underwater breathing apparatus represents a revolutionary development in the field of oxygen diving. The successful and reliable operation of such a device would offer many important advantages over existing types of self-contained underwater breathing outfits. Therefore, the evaluation of the oxygen control device was given first priority by the Navy Experimental Diving Unit.

In order to determine the operating characteristics of this device a series of tests was conducted to obtain data on the following characteristics:

- (1) Limits of oxygen range.
- (2) Reliability of senser calibration.
- (3) Ease of changing calibration.
- (4) Endurance of battery pack.
- (5) Flow of oxygen in liters per minute at various pressures.

All these tests were conducted in the dry Navy Experimental Diving Unit recompression chamber in order that close observations could be made and to prevent any damage to the unit as a result of accidental water leakage or excessively rough handling. The results of these tests are as discussed below.

(1) Limits of oxygen range

The limits of oxygen range (the maximum and minimum values of oxygen partial pressure for a given setting of the sensor) were determined by placing the complete oxygen control unit in the dry recompression chamber, increasing pressure, and noting the depth at which the sensor closed the electronically operated valve (maximum value), and then by reducing the chamber pressure and noting the depth at which the valve opened (minimum value). Three separate runs were made at this time, each run consisting of from 5 to 15 reversals of pressure. The results obtained from the three runs are tabulated on data sheet #1. A study of these data results in several interacting observations regarding the performance of the sensor unit. It is evident that the sensor unit was operating to control the oxygen partial pressure within acceptable limits. However, it is also evident that as each run progressed the maximum and minimum values of oxygen partial pressure at which the sensor operated became gradually less. While there was no readily evident cause for this gradual reduction in the partial pressure which caused operation of the sensor, several ideas are presented as possible causes. The first and most probable idea is that the drain on the "A" batteries was sufficient to cause a gradual reduction in the voltage output of these batteries. This is the 1 1/2-volt circuit which operates the light source to the photoelectric tube; thus any decrease in light intensity would cause a more rapid closing of the electronically operated valve. There is some evidence that a decrease in light intensity did occur as the run progressed but the decrease was determined solely by observation and no accurate measurements could be made. The fact that the maximum and minimum values of oxygen partial pressure at the start of run #2 were actually higher than at the beginning of run #1 could be explained by the fact that there was some delay in starting run #1 so that it is possible that the voltage was already somewhat reduced at the beginning of the run. Run #2 was conducted the next morning (25 July) using fresh 1 1/2-volt batteries, and run #3 was conducted that same afternoon (25 July) with approximately four hours between runs, which would permit at least partial battery recovery.

A second but less probable idea for the gradual decrease in the operating oxygen partial pressure is based on the possibility that as the run progressed the gradual reduction in oxygen bottle pressure resulted in a reduction in the pressure applied to the electronically operated valve. However, this seems somewhat improbable since a two stage regulator is installed between the oxygen bottle and the valve and at no time was there any evidence of malfunction of this regulator.

(2) Reliability of senser calibration

From the results of the three runs tabulated on data sheet #1, it is evident that the reliability of the senser calibration was entirely satisfactory during these runs. The overall average oxygen partial pressures in atmospheres were .600, .612, and .579 respectively for these runs, which are well within the accuracy range required.

(3) Ease of changing calibration of senser (original unit)

The senser recieved with this apparatus had been calibrated and set by the contractor prior to delivery to the Navy Experimental Diving Unit. However, verbal instructions were given the NEDU personnel concerning the method of changing the adjustment to increase or decrease the oxygen percentage. This adjustment involved rotating the light source (1 1/2-volt bulb) while maintaining it in the same horizontal and vertical plane.

Since there was no method of determining in advance how far to rotate the bulb it was necessary to recalibrate the senser after each trial until the desired value was obtained. In addition, it was practically impossible to retain the bulb in the same horizontal and vertical planes, since it was necessary to loosen the bulb support in order to rotate the bulb. As a result, range as well as calibration was changed. Several attempts were made by NEDU personnel to change the calibration without success, and it was necessary to return the senser to the contractor for re-calibration.

(4) Endurance of battery pack (original model)

The battery pack received with the original apparatus was entirely unsatisfactory in regard to endurance. The 1 1/2-volt supply was especially inadequate and could be depended on only for one-half hour of continuous trouble free operation. The 45-volt and 30-volt batteries appeared to have much greater endurance than the 1 1/2-volt batteries, but they too became exhausted after approximatley five to six hours use. The 1 1/2-volt circuit also gave trouble in that frequently the installation of new 1 1/2-volt batteries would cause the bulb to burn out; and, while the installation of a new bulb was not excessively difficult, it did result in a change in calibration of the unit.

(5) Flow of oxygen

The flow of oxygen through the electronic valve orifice at various pressures was determined by measuring the amount of gas flowing per minute at the exit from the valve. This was accomplished by installing a rubber tube at the whistle signal device connection and measuring the flow on the laboratory wet gas meter. In all tests from surface pressure to a depth of 99 feet, flow was found to be 8 liters per minute with the first stage of the regulator set at 250 psi and the second stage set at 50 psi.

During the months of August and September 1951 numerous attempts were made to calibrate the senser unit without success. In almost every instance it was determined that inadequate voltage on one of the three circuits was responsible for the failure of the unit to operate satisfactorily, the most frequent failure being the 1 1/2-volt circuit. Several types of 1 1/2-volt batteries were tried in the unit without success; in several instances these resulted in excessive voltage being applied to the light source, causing the bulb to burn out. Subsequent replacement of the light bulb would change the calibration of the unit so that recalibration was necessary.

It was determined during this period that there was appreciable current leakage through the metal battery case. This current leakage was successfully stopped by substitution of a plastic battery case for the metal case. However, on the first attempt to recalibrate the unit using the plastic battery case, it was discovered that the needle suspension was broken so that the effectiveness of the new case in prolonging battery life could not be evaluated at this time.

Since replacement of the needle was beyond the capabilities of the NEDU the entire oxygen control unit was returned to the contractor for repair and modification.

PART II

EVALUATION OF THE OXYGEN CONTROL DEVICE (MODIFIED MODEL)

The modified oxygen control device was delivered to the Navy Experimental Diving Unit on 1 November 1951 for further evaluation. The following modifications had been made by the contractor at this time:

(1) A new senser test body suspension was installed to replace broken suspension. of the test body (needle) was increased to prevent needle overswing and to provide for more rugged service. The nylon suspension filament had been pre-stretched and tested by a tensile loading of 32 grams.

(2) A completely new battery pack was designed and installed. The new battery pack incorporated the use of a plastic case 6 1/2" x 4" x 3 1/8". This much larger case permitted the use of an increased number of larger batteries. Theoretically the expected battery life was increased by a factor of 4 on the 45 volt and 60 volt circuits and 12 on the 1 1/2-volt circuit. All batteries were well insulated to prevent leakage between batteries and through the battery case. The following batteries were used to make up the battery pack: one 45-volt "B" battery (similar to Burgess Model N30); two 30-volt "B" batteries connected in series (similar to Ever Ready Model 413E); and eight 1 1/2-volt mercury "A" batteries (similar to Mallory Model RM-12).

(3) The light source circuit was modified to provide for a more constant voltage output with increased battery life. Modification consisted of installation of a resistor in the circuit to decrease the voltage applied to the light bulb from 1.5 volts to 1.2 volts and the use of an increased number of new type 1 1/2-volt "A" battery. The number of "A" batteries used was increased from 4 to 8. The new mercury type "A" battery was used to replace the previously used pen type "A" battery. These new batteries have a much greater life, and a rapid recovery time during their entire useful life.

(4) The light source was modified to incorporate the use of a double lens on the light source bulb. The purpose of this extra lens, which was cemented to the light bulb with transparent cement, was to narrow the light beam to the photo tube. In addition, the entire bulb and lens was masked with black opaque lacquer except for a single pin point opening through which the light could pass. It was anticipated that by narrowing the light beam striking the photo tube window the operating range of the sensor could be greatly reduced.

(5) The mechanism for calibration of the sensor was completely modified to allow for easy recalibration when required. The modification was accomplished by installing the light source (bulb) in a sliding support and holding it in parallel alignment with the photo tube window by spring tension. Two springs were used, one on either side of the sliding support. Calibration of the sensor was effected by means of set screws operating against the springs. This modification eliminated the necessity for loosening the bulb support, which had caused most of the calibration difficulties on the original model.

CALIBRATION OF THE SENSER

As received, the modified sensor had not been calibrated; therefore it was necessary to accomplish the calibration at the Navy Experimental Diving Unit prior to making any dives in the wet tank with the apparatus. Calibration of the sensor was accomplished by the method used for calibration of the previous unit. The procedure was as follows:

The oxygen control unit was placed in the dry recompression chamber and connected in the same manner as when used for diving, except that air was used in place of oxygen. Use of compressed air as a substitute for oxygen permitted a more accurate determination of the oxygen partial pressure which caused the sensor to operate. After the apparatus was set up, the recompression chamber lights were turned off to prevent outside light from affecting the photo tube, and pressure within the chamber was increased until the desired oxygen partial pressure was obtained (usually to a pressure of 3 atmospheres absolute for an oxygen partial pressure value of .63 atmospheres). The sensor was then adjusted by means of the set screw adjustment until closing of the electronic valve occurred at the oxygen partial pressure value of .63 atmospheres. Pressure within the recompression chamber was then decreased and a note made of the depth at which the electronic valve opened. The test was then repeated until the desired calibration range was obtained.

The modified sensor was calibrated by the foregoing method on 5 November 1951 with results as tabulated below:

<u>Senser Off;</u> <u>depth, feet</u>	<u>Oxy pp</u> <u>atm</u>	<u>Senser On;</u> <u>depth, feet</u>	<u>Oxy pp</u> <u>atm</u>	<u>Oxy pp</u> <u>Average</u>
66	.63	59	.585	.606
67	.636	59	.585	.610
66	.63	58	.579	.605
66	.63	59	.585	.606

From these results it is readily evident that a completely satisfactory calibration was attained and that the operating range of the sensor was greatly decreased from that of the previous model. No difficulties were encountered in making this calibration, which required approximately thirty minutes to accomplish.

RESULTS OF DIVES

During the period from 5 November until 21 November 1951, a total of four dives were made in the Navy Experimental Diving Unit wet tank using this apparatus. The results of these dives were as follows:

Dive #1

The first dive was made on 5 November to a depth of 66 feet in the NEDU wet tank. The purpose of this dive was to determine the operating characteristics of the oxygen control device underwater with the diver doing moderate work. It was conducted in the following manner. After donning the equipment, the diver entered the wet chamber and charged the apparatus with air from the air flask while still on the surface. He then connected the oxygen sample tube from the apparatus to the tank sampling connection which led to a Beckman model "D" oxygen analyzer mounted outside the tank. After connecting the sampling tube the diver entered the water, slowly submerging the apparatus in order that any leakage could be readily detected. A constant pressure was maintained on the apparatus during this period by charging the apparatus with air from the air flask. After a satisfactory test on the water tightness of the apparatus, pressure was put on the tank equivalent to a depth of 66 feet. Descent was made using air from the air flask to increase the volume of breathing medium as required by the increasing pressure.

At this depth the sensor switch and oxygen supply were turned on. The oxygen percentage at the bottom prior to turning on the oxygen supply was found to be 14 percent (.42 atm O₂ pp). Thus when the oxygen control unit was placed into operation it resulted in an immediate opening of the electronic valve to permit oxygen to enter the apparatus. The valve remained open until the oxygen partial pressure increased to the cut off value of 21 percent or .63 atmospheres at which time the sensor caused the valve to close, shutting off the oxygen supply to the apparatus. The opening and closing of the electronic valve was readily detected since the whistle could be easily heard by the diver when the valve was open and oxygen was being admitted to the apparatus.

During this dive, however, even though the senser continued to control the oxygen supply valve in a closed position, the oxygen partial pressure continued to increase. Thus it became obvious that internal oxygen leaks were causing a malfunction of the apparatus, and the dive was terminated. Disassembly of the apparatus disclosed that the oxygen bottle valve had developed a bad leak, allowing the oxygen partial pressure to increase despite the electronic valve being closed.

Dive #2

During the period of 5 November to 19 November 1951, repairs were made to the apparatus to correct the oxygen leaks and to provide for a more adequate water tight seal of the apparatus.

The second dive was made in exactly the same manner as the first and again to a depth of 66 feet. The results of this dive were identical to those obtained previously because continuous oxygen leaks again caused the oxygen partial pressure to increase far beyond the upper limit of the senser calibration. Disassembly of the unit showed that opening the oxygen flask resulted in an appreciable leakage of oxygen around the flask valve. This leak, being ahead of the electronic valve, permitted a continuous flow of oxygen into the apparatus.

Dive #3

The third dive was made on 20 November 1951 in the identical manner of the previous dives except that in this instance the depth of dive was 99 feet. Stops were made at depths of 33 and 66 feet to check the operation of the senser prior to descending to 99 feet. Descent to 33 feet was made on air supplied from the air flask, and the oxygen percentage was determined at this depth before the oxygen control unit was placed in operation. The percentage of oxygen as recorded on the Beckman Model D oxygen analyzer was 19 percent (.38 atmospheres O_2 pp). The senser unit and oxygen supply were then put into operation. The whistle sounded immediately, indicating an oxygen flow into the apparatus. This oxygen flow continued for approximately 30 seconds, at which time the senser caused the electronic valve to close. An oxygen percentage of 28 percent (.56 atm O_2 pp) was recorded at this time. Pressure was then increased to an equivalent depth of 66 feet and held at this point until an oxygen percentage was determined. Since air from the flask was used in making the descent it was found that the oxygen percentage was decreased to a value of 26 percent, as would be expected. The electronic valve remained closed during the descent and during the entire time at 66 feet.

Pressure was again increased to an equivalent depth of 99 feet and held at this value. Descent was again made on air from the flask. The oxygen concentration upon reaching the 99 foot depth was 30 percent, which was an increase of 4 percent over that determined at the 66 foot depth. At no time was there any evidence of the oxygen valve having

opened, which once again indicated internal oxygen leaks ahead of the electronic valve as the cause for the increased oxygen concentration. The diver remained at the 99 foot depth until the Beckman analyzer showed an oxygen concentration of 37 percent (1.48 atmospheres O_2 pp), at which time the dive was terminated. Upon disassembly of the apparatus, several small oxygen leaks were discovered in the oxygen system around the oxygen fittings ahead of the oxygen valve, which were once again the cause for failure. However, it is the opinion of this command that had there been no oxygen leak these three dives would all have been a complete success, because there was every indication that the oxygen control device was functioning in the proper manner.

Dive #4

The fourth dive was made on 21 November 1951 after a complete repair of the oxygen system had been made to eliminate any possibility of oxygen leaks. A new oxygen flask was installed at this time and a soap test made of all connections just prior to closing the apparatus.

The procedure for this dive was identical to the previous dives except that a direct descent to a depth of 66 feet was made. Descent was once again made on air and the oxygen concentration was determined before the oxygen control device was activated. The Beckman analyzer showed an oxygen concentration of 14 percent (.42 atm O_2 pp) at the time the sensor was turned on. The signal device immediately indicated flow of oxygen through the electronic valve, which was expected since the oxygen partial pressure was less than the calibrated setting of the sensor (.60 atm). However, as the oxygen concentration increased to and beyond this calibrated value, the electronic valve failed to close. As the concentration continued to increase at a rapid rate, it became obvious that the sensor was completely inoperable and the dive was terminated when the oxygen concentration reached a value of 70 percent (2.10 O_2 pp).

Examination of the sensor unit upon completion of the dive showed failure of the following components:

- (1) 1 1/2-volt bulb burned out.
- (2) Vacuum tube in 45-volt circuit inoperable.

Since repair of these components was beyond the capabilities of the Navy Experimental Diving Unit personnel, the complete oxygen control device was returned to the contractor for repairs.

RESULTS OF CALIBRATION EFFORTS DURING THE WEEK OF 25 NOV 1951:

The repaired oxygen control device was returned to the Navy Experimental Diving Unit on 26 November for calibration and further evaluation. However, during assembly of the senser unit the 1 1/2-volt bulb accidentally burned out as a result of contact with leads from the 60-volt circuit. Therefore, it was necessary to install a new bulb prior to continuing with the calibration.

Although installation of a new bulb was accomplished without difficulty, appreciable difficulty was encountered in attaching the double lens system to the bulb prior to installation. This is a tedious rather than difficult operation since the proper focus of light on the photo tube window is accomplished by a trial and error method and must be done in relative darkness to eliminate the effect of daylight on the photo tube when the circuit is energized. However, on a production model the replacement of a defective bulb could be accomplished in a routine manner by using a prefocused double lens bulb, which could be carried as a spare part.

Chamber calibration runs were made on 27, 28, and 29 November without success, although there were indications that only minor troubles were being encountered. A careful analysis of the unsuccessful calibration efforts indicated quite clearly that the following troubles were being encountered:

1. The hollow glass needle test body was sluggish, having a tendency to stick at each end of travel. This sluggishness was probably due to a collection of iron particles or dust on the suspension.
2. Circuit contacts were poor, especially in the 1 1/2-volt circuit. This was evidenced by the fact that any slight movement of the senser unit or battery pack would cause an appreciable change in light intensity. In fact, it was rather difficult to keep the light bulb lit at all, even though new battery plugs were installed.
3. Circuit voltages were reduced because of prolonged use of the battery pack. This was most evident in the 60-volt circuit after approximately ten hours of total operation.

It is considered that the sluggishness of the test body contributed primarily to the failure in effecting a satisfactory calibration. Since it was rather obvious that the sluggishness was caused by fouling of the test body suspension, it was decided to discontinue evaluation of the apparatus until a time when the contractor's representatives could be present to provide professional assistance in the evaluation. Consequently, no further work was done with the apparatus until the week of 28 January 1952 when three engineers from the Old Dominion Research and Development Corporation arrived at the Navy Experimental Diving Unit to assist in the evaluation of the apparatus.

RESULTS OF FINAL EVALUATION DURING THE WEEK OF 28 JANUARY 1952

The contractor's engineers arrived at the Navy Experimental Diving Unit on Monday, 28 January 1952 and work was immediately undertaken to continue the evaluation of the apparatus. The results obtained are discussed below for each day's work.

Work accomplished on 28 January 1952

In view of the sluggish action of the glass needle test body it was decided that in order to insure satisfactory performance of the oxygen analyzer the entire unit should be disassembled and thoroughly cleaned. Therefore, most of the day was spent at this task. In addition, it was decided to set up a bench calibration procedure to prevent any possibility of iron dust entering the unit from the air lines to the recompression chamber. Enclosure (6) is a photograph of the setup used in making the bench calibration. In this method, air and oxygen were bubbled through a flask containing water and into a Beckman Model D oxygen analyzer, where a continuous analysis of the gas mixture was obtained. The analyzed gas was then directed from the Beckman analyzer via the sample tube to the senser sample test chamber. The oxygen concentration of the sample was gradually increased from that of air to a predetermined concentration at which a closing of the electronic valve was desired. The necessary adjustment was then made by turning the adjusting set screw until closure of the electronic valve was noted. The oxygen concentration was then slowly reduced by cutting down on the oxygen supply and increasing the air supply until the reduction in oxygen partial pressure caused the electronic valve to open. This procedure was repeated until a satisfactory calibration of senser was obtained.

The cleaning of the test body suspension was accomplished without difficulty and after reassembly a calibration of the senser was made using the above described method, and the senser was adjusted to open the electronic valve at an oxygen partial pressure of .42 atmospheres and to close at .62 atmospheres. No dives were made this date.

Work accomplished on 29 January 1952

Two dives were accomplished on this date with the following results:

Dive #1

This dive was conducted in the same manner as the dives described previously. After checking for leaks descent was made to a depth of 33 feet on air with the senser and oxygen flask secured. The oxygen concentration upon reaching 33 feet was found to be 18 percent. The senser and oxygen flask were then turned on and the whistle immediately indicated oxygen flow into the apparatus. The senser and oxygen supply were secured at this depth when the Beckman analyzer showed an oxygen concentration of 34 percent. Descent was then made to a depth of 66 feet with no change in oxygen concentration. The senser and oxygen supply were again put into operation and once more the whistle sounded immediately. Oxygen concentration continued to increase until the dive was discontinued at a value of 78 percent (2.34 atm O₂ PP).

Upon disassembly of the apparatus it was determined that failure of the senser to operate properly was a result of an open 1 1/2-volt circuit. With the light bulb inoperative no light was available to energize the phototube circuit and therefore the electronic valve remained open. This condition was to be expected since the valve is normally open with the magnet de-energized.

Dive #2

Prior to making this dive the oxygen control unit was completely rewired to insure positive contact in all circuits. This problem of poor contacts, especially in the 1 1/2-volt circuit as previously mentioned, had continued to be a constant source of trouble. However, it was anticipated that this trouble would be eliminated by modifications made at this time. In addition to re-wiring the oxygen control unit, new 1 1/2-volt and 45-volt batteries were installed and the senser was recalibrated to operate in the range of 48-62 percent.

Once again the dive was conducted in the manner of all previous dives. Descent on air to 33 feet was followed by a short stop at this depth. Oxygen concentration upon reaching 33 feet was 18 percent. Senser and oxygen supply were turned on, and the whistle indicated oxygen flow as was expected. When oxygen concentration had increased to a value of 20 percent (.40 atm O₂ pp), descent to a depth of 65 feet was made without securing senser or oxygen supply. Oxygen concentration upon reaching 66 feet was 30 percent. The whistle continued to indicate an oxygen flow until oxygen concentration reached a value of 48 percent, at which

point the electronic valve closed. An oxygen concentration of 48 percent (1.44 atm O₂ pp) was well beyond the calibration setting and malfunction of the senser was suspected at this time. However, as oxygen percentages gradually decreased, descent was continued to a depth of 99 feet using air. The air flask had exhausted at 66 feet, requiring use of the surface breather from 66 to 99 feet to increase volume of breathing medium. Oxygen concentration upon reaching 99 feet was 39 percent (1.56 atm O₂ pp). The electronic valve remained closed at this depth and oxygen concentration continued to decrease slowly. At 28 percent an ascent to a depth of 66 feet was made. The diver remained at this depth until oxygen concentration decreased to 9 percent at which point the dive was terminated. Except for a momentary opening and closing of the electronic valve when the oxygen concentration recorded was 14 percent (.42 atm O₂ pp), the valve remained closed throughout this period. The momentary opening of the valve occurred when the diver shifted the apparatus on his back. Oxygen concentrations as recorded on the Beckman Model D oxygen analyzer during the progress of this dive are shown on data sheet #2.

Disassembly of the apparatus revealed that one of the photo tube connections had accidentally grounded against the senser cover and thus had prevented opening of the electronic valve. No other failure or discrepancies in the control unit were detected at this time.

The difficulties encountered as a result of grounds and shorts in the senser unit were not particularly surprising since it was recognized early in the evaluation that insulation of the various components one from another and from the cover itself was inadequate and a potential source of trouble. However, in a production model this deficiency could readily be corrected by increasing the physical dimensions of the unit to permit adequate insulation, or by moulding parts of the circuits into plastic.

Work accomplished on 30 January 1952

Prior to making any dives the entire apparatus was thoroughly checked to insure that all units and components were operating in an entirely satisfactory manner. In addition, the second stage pressure of the oxygen regulator was reduced from 50 psi to 20 psi in order to reduce the rate of oxygen flow through the electronic valve from 8 liters per minute to 3.9 liters per minute with the valve fully open. Previous dives had definitely indicated excessive oxygen flow when the valve was open, which resulted in excessive oxygen pressure within the apparatus. This excessive gas pressure in the apparatus (breathing bag) caused a tremendous increase in exhalation resistance with a resultant loss of gas around the boundaries of the face mask. It was felt that by decreasing the gas flow this problem would be at least partially corrected. The gas flow at the reduced second stage regulator pressure was checked by means of a laboratory spirometer and found to be constant in value.

The sensor was again recalibrated before this dive and adjusted to operate in the range of .8 to 1.0 atmospheres oxygen partial pressure, which is somewhat higher setting than previously used.

After completing the above work on the apparatus, a dive was made in the same manner as all previous dives with the following results.

Descent was made from the surface to 99 feet on air from the flask. However, as in several previous dives the air supply became exhausted before reaching 99 feet and it was necessary to increase the volume of gas in the breathing bag by taking in air through the surface breather on the mask. While such a procedure is easily accomplished in the Experimental Diving Unit tank, it would be impossible under submerged conditions. Therefore, it is obvious that the capacity of the air flask must be increased from the presently used .568 liter flask to a flask having at least double or triple this capacity.

Upon reaching 99 feet the sensor and oxygen bottle were turned on as in all previous runs. The oxygen percentage upon reaching this depth was found to be 14 percent (.56 atmospheres O_2 pp), so that the sensor immediately caused the electronic valve to open. Oxygen partial pressure increased gradually to the pre-set upon value at which time the oxygen valve closed. Moderate work, involving the lifting of a 68.5 pound weight 27.25 inches from the deck of the tank to a work bench and back again at a rate of five times a minute, was accomplished during this period to check on the adequacy of the 3.9 liter per minute oxygen flow. The diver reported that this flow seemed adequate and that no excessive pressure was built up in the apparatus.

The pressure on the tank was then reduced to a value equivalent to a depth of 66 feet and the work sequence repeated. A perusal of the data tabulated on data sheet #3 clearly indicates satisfactory operation of the oxygen control device.

After satisfactory operation of the apparatus was observed at the 66-foot depth, ascent was made to 33 feet and again the work sequence repeated. The reduction in oxygen partial pressure from 66 feet to 35 feet immediately caused opening of the oxygen valve, which was proper. This dive was terminated at 33 feet by exhaustion of the oxygen supply (the bottle was not fully charged at start of dive) rather than by malfunction of the apparatus.

This was an entirely satisfactory dive in all respects and proved conclusively that the automatic control of oxygen partial pressure at a constant pre-set value at varying depths is possible with this apparatus. Enclosure (7) is a graph of oxygen partial pressure plotted against time as determined by this dive. It is readily noted from this graph that the oxygen control unit was operating satisfactorily within the pre-set calibration range.

Work accomplished on 31 January 1952

The final two evaluation dives were made this date with the following results.

Dive #1

This dive was conducted in a somewhat different manner from previous dives in that the diver remained at a depth of 10 feet doing moderate work for a period of 15 minutes before descending to the 99 foot depth. The purpose of this procedure was to determine the effect of rapidly increasing depth after a prolonged period at shallow depth.

Immediately upon obtaining a check on the water tightness of the apparatus the diver turned on the senser and oxygen supply and made the descent to 10 feet on oxygen. He commenced work without delay at the rate of five works per minute.

During this 15 minute period both the signal element (whistle) and Beckman oxygen analyzer indicated the satisfactory operation of the senser within the calibration range of .65 to .84 atmospheres oxygen partial pressure. The oxygen flow of 3.9 liters per minute during the periods that the valve was open was just adequate for this type work and would have been inadequate for more strenuous work. A study of data sheet #4 and the graph of enclosure (8) clearly indicates the satisfactory performance of the oxygen control device during this period.

It will be noted that oxygen concentrations recorded on the Beckman analyzer do not correspond too well with the opening and closing of the electronic valve. This lag in Beckman readings was caused by:

- (1) The slow rate of gas flow through the sample tube to the Beckman oxygen analyzer (rate of flow was approximately 60 cc per minute).
- (2) The length of the sampling tube. It was necessary to use a sampling tube approximately 4 feet in length in order to provide for continuous sampling under conditions of work.

After completing the 15 minute work period at 10 feet, descent was made to a depth of 99 feet using air from the air flask as required to maintain an adequate breathing volume. Once again the air flask was exhausted before reaching 99 feet which again required use of the surface breather. Oxygen concentration upon reaching 99 feet found to be 42 percent (1.68 atm O_2 pp), which is well within the safe range of oxygen partial pressure.

Moderate work, as before, was started immediately. As was expected, the oxygen valve remained closed and oxygen partial pressure gradually decreased. However, at an oxygen partial pressure of 1.44 atm (see data sheet #4) the oxygen valve opened and began supplying oxygen. The opening of the valve at this point indicated a definite malfunction of the sensor since the oxygen partial pressure was much higher than the calibrated cut off value. The valve remained open and the oxygen concentration increased gradually. Work was continued during this period and the diver reported more than adequate gas flow for easy breathing, so that exhalation resistance increased appreciably with some loss of gas around the face mask boundaries. Since this was under conditions of continuous oxygen flow it is possible that under conditions of proper sensor control the 3.9 liter flow would be satisfactory for doing moderate work.

When the oxygen partial pressure increased to a value of 1.68 atmospheres the diver was brought up to a depth of 10 feet and the work sequence continued. Immediately upon commencement of work the oxygen valve closed (.70 atm O_2 pp) and remained closed for approximately five minutes.

However, upon starting another work period the valve again opened (.86 atm O_2 pp), above the calibrated setting. Oxygen concentration continued to increase until the dive was terminated at an oxygen partial pressure of 1.12 atmospheres.

In the light of previous experience with the apparatus, a malfunction of the 1 1/2-volt circuit or light bulb was suspected as the cause for the erratic operation of the sensor during the last half of the dive. A loose connection seemed to be the most probable cause of the malfunction, since shifting of the apparatus during work periods seemed to have a definite effect on its operation. Upon disassembly of the apparatus this was found to be true.

Dive #2

After repairing the loose wire in the 1 1/2-volt circuit and thoroughly checking the entire apparatus, a final endurance dive of one hour was made at a depth of 20 feet. No change was made in the calibration range of the previous dive, .65 to .84 atmospheres oxygen partial pressure.

Descent to 20 feet was made on air as before. At this depth the sensor and oxygen supply were turned on. A moderate work sequence of five works per minute for a period of ten minutes followed by a five minute rest period was maintained throughout the dive. A continuous gas sample was drawn from the apparatus for analysis on the Beckman Model D oxygen analyzer as on all previous dives.

A study of data sheet #5 and enclosure (9) indicates that again during this entire dive the oxygen control device operated in a satisfactory manner. However, it is readily evident from the graph (enclosure (9)) that as the dive progressed the calibration setting had a tendency to shift to slightly higher values for both the opening and the closing of the oxygen valve.

This type of malfunction was anticipated with the present sensor and the cause well recognized. It was noted during the many times that the sensor was recalibrated, that the calibration adjustment was extremely sensitive and that only 1/32 of a turn on the adjusting screw was required to change the calibration value by 15 percent at the higher values used in all the dives made during the final week of the evaluation. Therefore, the slightest change in spring tension caused either by a shock or by a temperature change is sufficient to account for the variation observed during this dive. This is especially true since a reduction in spring tension causes an increase in the operating limits. However, this is not a serious problem and can be readily corrected by a modification of the adjusting mechanism to permit the use of heavier springs and a less critical adjustment.

During the major part of this dive the 3.9 liter per minute oxygen flow was adequate for the moderate work being done. However, it was necessary on several occasions, just before the valve opened, to add air from the air flask in order for the diver to obtain a full inhalation. Therefore, it would appear that either gas flow rate or breathing bag volume, and perhaps both, should be increased to insure an adequate breathing volume under varying conditions of work. It is highly recommended that this problem be fully investigated prior to manufacture of any future apparatus of this type.

The rate of oxygen consumption during this dive was determined to be 1 liter per minute, which compares favorably with other self-contained underwater oxygen breathing apparatus evaluated at the Navy Experimental Diving Unit under identical work conditions. Based on oxygen consumption at this rate the present 1.46 liter flask when charged to 2000 psi would have an endurance time of approximately two hours.

PART III

EVALUATION OF DIVING CHARACTERISTICS

The constant oxygen partial pressure self-contained underwater breathing apparatus (Marion device) evaluated in this report is strictly an experimental model and is in no sense a prototype model. In the present model the primary object was to evaluate the feasibility of this revolutionary device in controlling oxygen partial pressure at a constant pre-set value; evaluation of the diving characteristics of the apparatus was more or less incidental to the investigation.

The use, for the first time, of sensitive and fragile electronic gear as a part of an underwater breathing device required that this equipment be mounted within a water proof rigid housing. Therefore, the present apparatus bears no resemblance to any known apparatus, as is readily seen from enclosure (1), (2), and (3). The equipment appears to offer many advantages, although certain modifications and improvements are required before it can be considered satisfactory as an underwater diving apparatus. The diving characteristics, evaluated together with results and discussion, follow.

COMFORT

The comfort of this apparatus, except for the old type Lambertsen face mask which was supplied with the outfit, was surprisingly good. The outfit was somewhat heavy and cumbersome when worn for long periods out of water but when submerged was quite comfortable with approximately 2 pounds negative buoyancy. The weight of the complete apparatus out of water was 42 pounds.

The harness was so designed as to provide freedom of motion both in swimming and diving, but had a tendency to chafe the shoulders when worn for long periods. It is recommended that the shoulder straps be padded to provide for greater comfort.

As mentioned previously, the mask supplied by the Bureau of Ships for use with this apparatus was an old type Lambertsen, practically worn out. As a result, the mask developed leaks and was generally uncomfortable during long periods of use. It was eventually replaced with the new type Lambertsen mask, which provided much improvement in comfort.

BREATHING RESISTANCE

During all dives made with this apparatus the breathing resistance (especially exhalation resistance) was found to be excessive to the point of being unsatisfactory in this characteristic. Actually it was found that under certain conditions expiration pressure reached such a high value that it was impossible for the diver to exhale into the breathing bag against this excessive pressure so that all expired gas escaped around the face mask boundaries. Therefore, it was necessary to wear the face mask with a fairly loose fit in order to exhale at all under these conditions. Since the apparatus was so obviously unsatisfactory in this characteristic no actual measurements were made to determine the exact peak expiration pressures developed.

Maximum expiration pressure was evident when the following combination of conditions was encountered:

- (1) Apparatus submerged in water.
- (2) Oxygen valve open with oxygen flowing at a rate of 8 liters per minute.
- (3) Diver taking deep breaths as a result of exertion.

Maximum inspiratory pressure was evident when the following combination of conditions were encountered:

- (1) Apparatus submerged in water, with diver on his stomach.
- (2) Oxygen valve closed with no oxygen flow.
- (3) Diver taking deep breaths as a result of exertion.

It was noted on several occasions that when the electronic valve remained closed for long periods the volume of gas in the breathing bag gradually decreased to the point where it was no longer possible for the diver to obtain a full inhalation. This was especially true during periods of moderate work. It was under such conditions that inspiratory pressures reach a peak. However, adding air from the flask to increase the volume of gas in the bag always reduced breathing resistance to normal values.

As mentioned previously in this report, an attempt was made to correct this unsatisfactory condition at least partially by reducing the rate of oxygen flow through the valve from 8 liters per minute to 3.9 liters per minute. This reduction in oxygen flow resulted in a definite improvement in maximum expiration pressures developed during prolonged periods of full oxygen flow. Actually there was no excessive buildup of pressure during periods when moderate work was being accomplished but there was still some evidence excess pressure during rest periods.

The change in the rate of oxygen flow did not appear to have any effect whatsoever on the inhalation resistance encountered. This, however, was expected since increased resistance to inspiration was evident only when no oxygen was being admitted to the breathing bag and when gas volume in the bag was low. Therefore, it would appear that in order to correct this condition the capacity of the breathing bag should be increased.

In addition to the factors listed above as effecting breathing resistance, it was observed that several other factors also contributed to the rather high normal breathing resistance of the apparatus. They were:

- (1) The rather inflexible rubber material used in the construction of the breathing diaphragm.
- (2) Restriction of water flow through the outer shell of the apparatus in way of the breathing diaphragm.
- (3) The requirement for mounting the apparatus on the diver's back.

The first two factors can be readily corrected to provide for greatly reduced resistance in breathing. In the first instance use of a light-weight flexible material should correct this problem. In the second instance, use could be made of a rigid wire mesh screen to protect the diaphragm.

instead of the presently used metal plate with half-inch drilled openings. Such a rigid screen would appreciably reduce the restricted water flow in and out of the shell and therefore reduce breathing resistance by a like amount. The third factor, however, does not lend itself to easy solution because it involves the same problems encountered in all back mounted outfits, namely, the effect of differential water pressure which varies with the diver's or swimmer's position.

BOTTLE CAPACITY (Air and Oxygen)

The apparatus used during this evaluation required the use of both an air and oxygen supply. The air was used to maintain the required breathing medium volume during descent and to provide makeup on the bottom when the breathing medium volume was reduced to the extent that a full inspiration was difficult. Oxygen was used as required to maintain a constant oxygen partial pressure. Both oxygen and air were supplied from separate flasks mounted within the watertight case.

The capacities of the oxygen and air flasks were measured by discharging the bottles into the laboratory spirometers and were found to be 1.46 liters and .568 liters respectively.

During practically all evaluation dives, the capacity of the air flask was inadequate for the purpose intended. In nearly every instance the air flask supply became exhausted before the dive was completed, requiring addition of air through the mask surface breather to maintain adequate breathing volume. As mentioned previously this was possible during dives conducted in the Navy Experimental Diving Unit wet tank but would have been impossible during dives in open water. Therefore, it is recommended that the air flask capacity be increased by a factor of three on all future models of this apparatus.

It was determined during the endurance dive made on 31 January that when moderate work was being accomplished the oxygen flask had a capacity sufficient for approximately two hours use. Oxygen consumption during this dive was at a rate of 1 liter per minute. Thus, it is obvious that under swimming conditions, where an oxygen consumption of at least 1 liter per minute can be anticipated, the endurance of the outfit would be reduced to about one hour. This is certainly an unsatisfactory endurance and, therefore, the capacity of the oxygen flask should also be increased by a factor of three.

The flasks presently used are capable of being charged to a pressure of 2000 psi.

CO₂ AB ORBENT CANISTER

A standard old style Lambertsen canister was used on this apparatus to absorb the carbon dioxide produced by the diver. During all evaluation dives the performance of this canister was satisfactory and at no time did carbon dioxide concentration build-up to a dangerous level. However, no endurance run was made to determine canister life since any modified model of this apparatus would incorporate the use of an entirely different canister.

CONCLUSIONS

In general, the evaluation of the constant partial pressure oxygen underwater breathing apparatus was quite satisfactory and much very valuable information was gained. The automatic control of oxygen partial pressure at a constant pre-determined value is a new and revolutionary development in the field of oxygen diving and therefore the conclusions drawn as a result of this evaluation have historical as well as technical value. The following specific conclusions are based entirely on the results of this evaluation.

1. The principle of automatic control of oxygen partial pressure at a constant pre-determined value is sound and can successfully be applied to the control of oxygen partial pressure in a self-contained underwater breathing apparatus.
2. The ability of the oxygen control device to maintain a constant oxygen partial pressure at a pre-set value was conclusively demonstrated by several dives made at varying depths up to a depth of 99 feet.
3. The control range, that is, the oxygen concentrations which resulted in the opening and closing of the electric valve, was satisfactory. The range was found to be around 25 percent with calibration for oxygen partial pressures less than .6 atmospheres and 15 percent with calibration for oxygen partial pressures more than 0.6 atmospheres.
4. The calibration of the sensor can be readily accomplished by experienced personnel using the simple laboratory setup shown in enclosure (6). Recalibration of the sensor to operate at any desired oxygen concentration is accomplished in the same manner and requires about 20 to 30 minutes to complete the operation. The instrument is extremely sensitive and, therefore, it is highly recommended that adjustment not be attempted by inexperienced personnel.

5. The modified battery pack using the batteries listed on page 3 of this report and shown in enclosure (4) has an effective life of at least eight hours with continuous operation and approximately sixteen hours with intermittent operation. The 1 1/2-volt "A" batteries have the shortest life and are controlling. The 45-volt battery has an estimated life in excess of twenty-four hours and the two series connected 30-volt batteries have an estimated life in excess of forty-eight hours. All the above estimates are based upon the use of fresh batteries.

6. The oxygen analyzer as modified and used in the final evaluation dives requires further modification to improve the reliability. Practically all the troubles encountered were caused by the repeated malfunction of certain components, and it is these components which require additional modification to insure satisfactory operation of the outfit for long periods of continuous use. Additional modification of the following components are required:

- (1) Calibration mechanism, to prevent creep and to decrease the adjustment sensitivity.
- (2) Circuit wiring, to provide more adequate insulation and positive circuit contacts.
- (3) Senser case, to provide more adequate protection against entry of dust and iron particles into the test cell.

7. The ruggedness of the senser unit is surprisingly satisfactory considering the delicate suspension of the test body and the sensitivity of electronic circuits. During the entire evaluation of the modified oxygen control device no malfunction of the oxygen analyzing unit was encountered as a result of rough handling. Only the normal care demanded of any delicate electronic instrument is required.

8. The operation of the electronic valve was satisfactory insofar as the valve itself is concerned. Every malfunction of this valve encountered during the evaluation was caused by a circuit failure in the senser unit.

9. The operation of the oxygen regulator was entirely satisfactory at the pressures encountered in this evaluation.

10. The signal element whistled satisfactorily at all depths up to 99 feet with an oxygen flow rate of 8 liters per minute. However, with an oxygen flow rate of 3.9 liters per minute performance of the signal element was unsatisfactory beyond a depth of 20 feet. Unsatisfactory performance was indicated by the inability of the diver to hear the sound of the whistle.

11. An oxygen flow rate of 8 liters per minute (oxygen valve open) is excessive, resulting in a loss of oxygen around the boundaries of the face mask on account of excessive exhalation pressure.

12. An oxygen flow rate of 3.9 liters per minute (oxygen valve open) is slightly inadequate for conducting hard work but does not produce excessive exhalation pressures.

13. Breathing resistance of the apparatus is slightly unsatisfactory under all conditions and positively excessive under certain conditions.

14. The capacity of both oxygen and air flasks is inadequate and should be increased.

15. Absorption of carbon dioxide in the Lambertsen canister was satisfactory during this evaluation but no endurance runs were made.

16. Endurance of the present apparatus is approximately two hours under conditions of moderate work with an average oxygen consumption of 1 liter per minute.

17. Comfort of the apparatus is good in all submerged positions. Some chafing was encountered around the arm pits during several dives of long duration.

18. The method of accomplishing water tight closure of the apparatus is unsatisfactory and requires modification.

RECOMMENDATIONS

Based on the information gained as a result of this evaluation the following recommendations are made:

1. That the entire apparatus be remodified to correct the deficiencies listed in this report under conclusions.

2. That upon completion of these modifications the apparatus again be evaluated by the Navy Experimental Diving Unit. It is recommended that special attention be given at that time to determine the following characteristics in addition to those determined in the present evaluation:

- (1) Depth of most efficient operation.
- (2) Most desirable oxygen partial pressure for the recommended operating depth.
- (3) Exposure time at the recommended depth, and the oxygen partial pressure which would require no decompression.

3. That in modifying the oxygen control device the calibration adjusting screw be located outside the sensor case to prevent entry of dust or other foreign matter into the case while making necessary adjustments.

4. That breathing resistance be reduced under all conditions to a value not in excess of two inches of water.

5. That the depth limitation be in the range of 60 to 100 feet.

6. That oxygen and air flask capacity be increased by a factor of 3 or more.

7. That a new type face mask, preferably of the modified MSA type, be used on any future apparatus.

LIMITS OF OXYGEN RANGE*
(ORIGINAL MODEL)

RUN NO. 1				RUN NO. 2				RUN NO. 3					
DEPTH SENSER OFF	02 PP ATM	DEPTH SENSER ON	02 PP ATM	DEPTH SENSER OFF	02 PP ATM	DEPTH SENSER ON	02 PP ATM	DEPTH SENSER OFF	02 PP ATM	DEPTH SENSER ON	02 PP ATM	DEPTH SENSER OFF	02 PP ATM
77	.700	51	.533	85	.752	60	.592	80	.672	55	.719	55	.561
75	.688	50	.529	80	.719	57	.573	76	.646	52	.693	52	.542
73	.674	48	.514	77	.700	55	.561	75	.630	50	.688	50	.529
73	.674	47	.510	75	.688	52	.542	74	.615	49	.682	49	.522
72	.668	47	.510	74	.682	50	.529	73	.606	47	.674	47	.510
				72	.668	49	.522	72	.595	46	.668	46	.503
				72	.668	47	.510	71	.589	45	.662	45	.496
				71	.662	45	.496	71	.579	44	.662	44	.491
				69	.649	45	.496	70	.572	43	.656	43	.484
								69		42	.649	42	.477
								69		41	.649	41	.471
								68		40	.643	40	.465
								68		39	.643	39	.458
								67		38	.637	38	.452
								67		38	.637	38	.452
Ave.	681		.519	.688			.536				.664		.494
Overall Ave.		600		.612						.579			

*Compressed air used in Oxygen Bottle to supply pressure on the electrically operated valve.

DATA SHEET NO. 2

OXYGEN CONCENTRATION DETERMINED DURING PROGRESS OF DIVE NO. 2 ON 29 JANUARY 1952. (Continuous breathing media sample drawn through Beckman Model D Oxygen Analyzer mounted outside wet tank).

% O ₂ in BREATHING MEDIA (PP)	DEPTH FEET	REMARKS	% O ₂ in BREATHING MEDIA (PP)	DEPTH FEET	REMARKS
21 (.21)	Surface	Senser Off	28 (.84)	99-66	Senser On
18 (.36)	33	Senser On	28 (.84)	66	Valve Closed
18 (.36)	33	Valve Open	27 (.81)	66	
19 (.38)	33		27 (.81)	66	
20 (.40)	33		26 (.78)	66	
22 ---	33-66		24 (.72)	66	
30 (.90)	66		23 (.69)	66	
34 (1.02)	66		22 (.66)	66	
38 (1.14)	66		22 (.66)	66	
42 (1.26)	66		21 (.63)	66	
44 (1.32)	66		20 (.60)	66	
48 (1.44)	66	Senser On	16 (.48)	66	Senser On
48 (1.44)	66	Valve Closed	14 (.42)	66	Valve Open
46 (1.38)	66		13 (.39)	66	Senser On
46 (1.38)	66		12 (.36)	66	Valve Closed
45 (1.35)	66		11 (.33)	66	
44 (1.32)	66		10 (.30)	66	
43 (1.29)	66		9 (.27)	66-20	Dive term inated
42 (1.26)	66				
40 (1.20)	66				
39 (1.17)	66-99				
39 (1.56)	99				
38 (1.52)	99				
36 (1.44)	99				
34 (1.36)	99				
32 (1.28)	99				
31 (1.24)	99				
30 (1.20)	99				
29 (1.16)	99				
28 (1.12)	99				

NOTE:
Calibration setting
.48 - .62 atmospheres O₂
partial pressure.

OXYGEN CONCENTRATION DETERMINED DURING PROGRESS OF DIVE NO. 1 ON 30 JANUARY 1952. (Continuous breathing media sample drawn through Beckman Model D oxygen analyzer mounted outside wet tank). Moderate Work: 58-10W

% O ₂ IN BREATHING MEDIA (PP)	DEPTH FEET	REMARKS	% O ₂ IN BREATHING MEDIA (PP)	DEPTH FEET	REMARKS
21 (.21)	Surface	Senser Off	24 (.72)	66	Senser On
		O ₂ Secured	25 (.75)	66	Valve Open
14 ---	Surf. 99	Senser On	26 (.78)	66	
15 (.60)	99	Valve Open	27 (.81)	66	
16 (.64)	99		28 (.84)	66	
17 (.68)	99		29 (.87)	66	
18 (.72)	99		30 (.90)	66	
19 (.76)	99		32 (.96)	66	
20 (.80)	99		33 (.99)	66	
21 (.84)	99		34 (1.02)	66	
23 (.92)	99		35 (1.05)	66	Senser on - Valve Closed
24 (.96)	99		35 (1.05)	66	
25 (1.00)	99		35 (1.05)	66	
26 (1.04)	99		34 (1.02)	66	
		Senser On	34 (1.02)	66	
25.5 (1.02)	99	Valve Closed	35 -----	66-33	Senser on - Valve Open
24 (.96)	99		36 (.72)	33	
---	99-66		37 (.74)	33	
			38 (.76)	33	
			39 (.78)	33	
			40 (.80)	33	
			41 (.82)	33	
			42 (.84)	33	
			42 (.84)	33	Dive terminated due to exhaustion of O ₂ supply.

NOTE:
Calibration setting .8-1.0 atmospheres O₂ (partial press pressure).

DATA SHEET NO. 4

OXYGEN CONCENTRATION DETERMINED DURING PROGRESS OF DIVE NO. 1 ON 31 JANUARY 1952. (Continuous breathing media sample drawn through Beckman Model D oxygen analyzer mounted outside the wet tank). 5R - 10W

% O2 IN BREATHING MEDIA (PP)	DEPTH FEET	REMARKS	%O2 IN BREATHING MEDIA (PP)	DEPTH FEET	REMARKS
21 (.21)	Surface	Senser On -	40 (1.60)	99	
50 (.50)	Surface	Valve Open	41 (1.64)		
60 (.60)	Surface		42 (1.68)		
65 (.65)	Surface		43	99-66	
69 (.69)	Surface	Valve Closed	44	66-10	
68 (.68)	Surface		47	10	
64 (.83)	10		48	10	
62 (.81)	10		50 (.65)	10	
60 (.78)	10		52 (.68)	10	
58 (.75)	10		54 (.70)	10	Valve Closed
56 (.73)	10		56 (.73)	10	
55 (.72)	10		59 (.77)	10	
54 (.70)	10		62 (.81)	10	
53 (.69)	10		63 (.82)	10	
51 (.66)	10		64 (.83)	10	
50 (.65)	10		65 (.85)	10	
49 (.64)	10	Valve Open	65 (.85)	10	
48 (.62)	10		66 (.86)	10	
49 (.64)	10		66 (.86)	10	
50 (.64)	10		66 (.86)	10	Valve Open
51 (.66)	10		68 (.88)	10	
52 (.68)	10	Valve Closed	69 (.90)	10	
55 (.72)	10		70 (.91)	10	
59 (.77)	10		71 (.92)	10	
62 (.81)	10		72 (.94)	10	
64 (.83)	10		73 (.95)	10	
66 (.86)	10		74 (.96)	10	
68 (.88)	10		75 (.98)	10	
67 (.87)	10		76 (.99)	10	
66 (.86)	10		77 (1.0)	10	
62 (.81)	10-99	Descent on air	78 (1.01)	10	
42 (1.68)	10-99		80 (1.04)	10	
40 (1.60)	10-99		82 (1.07)	10	
39 (1.56)	10-99		84 (1.09)	10	
37 (1.48)	10-99		86 (1.12)	10-Surf	Valve Closed
38 (1.52)	10-99				
39 (1.56)	10-99				

NOTE: Calibration setting .65 - .84 atmospheres oxygen partial pressure.

DATA SHEET NO. 5

OXYGEN CONCENTRATION DETERMINED DURING PROGRESS OF 20 FOOT ENDURANCE DIVE MADE ON 31 JANUARY 1952. (Continuous sampling on Beckman Model D oxygen analyzer). Samples every 30 seconds (approximately). Depth: 20 ft Duration: 1 hr 5R - 10W

%O ₂	O ₂ PP	POSITION OF VALVE	%O ₂	O ₂ PP	POSITION OF VALVE	%O ₂	O ₂ PP	POSITION OF VALVE
44	.707	Open	52	.835		61	.980	
40	.642		53	.851		60	.964	
42	.675		52	.835		59	.948	Open
43	.691		51	.819		56	.899	
44	.707		50	.803		54	.867	
46	.739		49	.787		53	.851	Closed
47	.755		48	.771		55	.883	
48	.771		47	.755		56	.899	
49	.787		46	.739		59	.948	
50	.803		45	.723		60	.964	Open
51	.819	Closed	44	.707		63	1.012	
51	.819		43	.691		54	1.028	
50	.803		42	.675	Open	66	1.060	
50	.803		44	.707		67	1.076	
49	.787		48	.771		68	1.092	Closed
48	.771		53	.851		69	1.108	
47	.755		54	.867		70	1.124	
46	.739		55	.883		71	1.140	
44	.707		56	.899		71	1.140	
43	.691		57	.915		70	1.124	
42	.675		58	.931		69	1.108	
41	.658		59	.948		68	1.092	
40	.642	Open	60	.964	Closed	66	1.060	
39	.626		61	.980		62	.996	
38	.610		62	.996		61	.980	
36	.578		63	1.021		59	.948	
35	.562		64	1.028		57	.915	
34	.546		65	1.044		56	.899	
38	.610		64	1.028		56	Ascent to	
42	.675		63	1.012			Valve surface	
46	.739		*49	.787	Open		Open.	
48	.771	Closed	52	.835				
50	.803		54	.867	Closed			
51	.819		56	.899				
52	.835		58	.931				
53	.851		59	.948				
53	.851		60	.964				
			61	.980				

*Breathing volume low - 1 breath surface air added.
 O₂ used 800 psi. Ave. 1 liter per minute.

1. Photograph - Internal general arrangement
2. Photograph - Flasks, canister, and valves
3. Photograph - Battery pack and sensor unit
4. Photograph - Batteries
5. Diagram - Wiring schematic
6. Photograph - Laboratory calibration set-up
7. Graph - Oxygen partial pressure versus time of dive at varying depth for dive #1, 1/30/52.
8. Graph - Oxygen partial pressure versus time of dive at varying depth for dive #1, 1/31/52.
9. Graph - Oxygen partial pressure versus time of dive at varying depth for dive #2, 1/31/52.

ENCLOSURES









