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DEVELOPMENT OF AN OPEN CIRCUIT CRYOGENIC LIFE SUPPORT SYSTEM FOR USE IN NEUTRAL BUOYANCY SPACE SIMULATION.

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ABSTRACT: Marshall Space Flight Center has a need for a self contained underwater life support system which can supply a breathing mixture to the neutral buoyancy test subject, without the need for a surface tethered supply line. A prototype system has been developed which utilizes a mixture of liquid oxygen and liquid nitrogen contained in a single supply tank. Development and testing has shown that this system will supply the quantity and quality of gas required under completely controlled and predictable conditions to depths of at least 60 feet.

KEY WORDS: Neutral buoyancy, space simulation, cryogenics, liquid oxygen, liquid nitrogen, liquid air.

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INTRODUCTION

Present neutral buoyancy space simulation techniques still model the tethered astronaut type of mission. Recent lunar surface operations and many future space missions under zero and sub-gravity conditions show the necessity for space simulation techniques which can model, with high fidelity, the umbilical-free astronaut missions. The present umbilical is used as the suit gas supply line. Therefore, a major type of equipment which is required to meet umbilical-free operations is a self-contained underwater breathing unit (SCUBA).

The Manufacturing Engineering Laboratory of the Marshall Space Flight Center has just completed the development of such a prototype system.

In order to develop the simplest system possible, it was decided to develop this backpack to be compatible with present suit systems in use in neutral buoyancy testing. This requirement results is retaining both the open circuit suit gas system and present suit through-flow gas rates. This combination could not be met without excessive weight and volume in a backpack using high pressure gas storage. Cryogenic liquid gas storage at subcritical pressure and high compressive potentials offered high storage efficiency without excessive weight or volume penalties. Further operational simplification was obtained by dictating that the diluent gas constituent be contained within a single liquid cryogen mixture. Neutral buoyancy depths easily allow choice of nitrogen as the diluent gas. Therefore the original design objective was for a single liquid mixture of liquid oxygen (LOX) and liquid nitrogen (LN_2) to be stored in a cryogenic system to feed the open circuit neutral buoyancy suit.

DESIGN REQUIREMENTS

Several design boundary conditions were established prior to starting this project; for principal importance were: (1) safety of operation, and (2) simplicity. Since the proposed apparatus must eventually be man-rated, the first condition follows as a natural consequence. The second requirement is merely a logical step towards achieving an operational state as soon as possible.

From these two basic conditions were developed certain specific design requirements:

1. The prototype was to be a breathing system of the "open circuit" type. "Open circuit" refers to the fact that the supply gas is dumped overboard after only one pass through the pressure suit. This system is currently used in Marshall Space Flight Center (MSFC) neutral buoyancy operations with an umbilical connection supplying a continuous flow of air through the pressure suit. Physiologically, this is the safest and simplest system; however, in addition to compromising simulation fidelity it is highly wasteful of the gases being supplied.

2. One hour duration was established as a target operational time for a single charging of the cryogenic tank.

3. Present suit through-flow rates of 5.0 ACFM (actual cubic feet per minute) were to be maintained at all depths. This means that as depth is increased, flow rate must also be increased to maintain 5.0 ACFM through the suit. If 45 ft. is established as the maximum operational depth, then the maximum standard cubic feed per minute (SCFM) rate on the bottom will be 2.36 times the surface rate, or 11.8 SCFM. In addition, it was felt that flow rates should be adjustable by the diver. From these considerations, a maximum flow capability of 16 to 18 SCFM was finally selected.

4. A cryogenic storage system was to be employed using a mixture of liquid oxygen (LOX) and liquid nitrogen (LN_2) in a single dewar. Cryogenic storage is necessary in order to supply the relatively large quantity of gas required.

5. Human safety and comfort parameters (breathing gas temperature, oxygen partial pressure, suit cooling, etc.) were to be maintained within the following limits:

   (a) Air temperature should be maintained at a comfortable level between 68°F and 80°F.

   (b) Oxygen partial pressure (PO_2) should be held within acceptable physiological limits. The minimum PO_2 of 0.20 atmosphere (152 mm Hg) is the lowest allowable. The maximum PO_2 is less clearly defined; however, the Marine Technology Society has set a PO_2 of 1.33 atmospheres (1010.8 mm Hg) as the upper limit for continuous exposure. Other equally well qualified sources have set this figure at 1.25 atmospheres (950 mm Hg). In general, the spaceflight environmental control system (ECS) limits for maximun PO_2 have been set lower than either of these figures. The problem of maximum PO_2 is simpler in cabins sealed for spaceflight. These cabins have a total pressure which is 1.0 atmosphere or less. The hyperbaric PO_2 problem found in submerged operations is more difficult than for space cabins. With preset gas ratios, such as with air or any single liquid cryogen, the minimum (hypoxic) surface limit selected also presents the depth PO_2 curve. Therefore, under conditions of submergence with constant ratio gas mixtures a realistic maximum may well be those chosen by the quoted diving oriented-sources.

As a design goal, the PO_2 range from 0.20 atmosphere to 1.0 atmosphere was selected for this work.

THEORETICAL CONSIDERATIONS

Initial studies showed a major problem to be the positive control and delivery of safe oxygen partial pressures. Several important theoretical aspects relating to the overall problem are outlined in the following sections.

A. Oxygen Partial Pressure (PO_2) Control

In a vessel containing a cryogenic mixture of liquid oxygen and liquid nitrogen, the partial pressures of the individual gasses over the liquid components have been shown to obey Raoult's Law. This law, which applied for all possible concentrations, states that at any given constant temperature the partial pressures of the components of a mixture are equal to the mole fraction of the component multiplied by its vapor pressure in the pure state at the temperature of the liquid.

The liquid boiling and vapor condensing curve for oxygen and nitrogen mixtures is shown in Figure 1 and indicates that at 1 atmosphere pure nitrogen is saturated at about -320°F (-195°C) and pure oxygen is saturated at -298°F (-183°C). In a binary mixture the simple terms "equilibrium or saturation temperature" do not exactly apply. In such a mixture, addition of heat and resulting liquid vaporization will shift both the mixture temperature and the gas and liquid phase composition. However, standard engineering terms are used throughout this section in reference to binary mixtures.

As an example consider a binary liquid mixture of 22% oxygen and 78% nigrogen contained as shown in Figure 1. The saturation temperature is about -317°F (-194°C). Under these conditions, this specific binary liquid mixture has in equalibrium with it a gas phase which contains only 8% oxygen which is well into the dangerous anoxic level. As this binary mixture continues to absorb heat, its sensible heat gain and subsequent temperature rise cause a disproportionate change in nitrogen and oxygen compositions. More of the liquid nitrogen boils off, resulting in a constant oxygen enrichment of the liquid phase, until the liquid is finally 100% oxygen.

As can be seen from the example above, any attempt to breathe the gas phase over the liquid mixture would be dangerous. From the analysis, it would seem possible to produce a gas phase containing 22% oxygen by starting out with a 50-50 liquid mixture. However, as useage continued, the partial pressure of oxygen would soon increase to a dangerous level especially in diving conditions. Thus, the situation in which a breathing gas phase is derived from a "pool" of a binary cryogen liquid mixture is undesirable. Such a situation will be inherently unstable and unpredictable with respect to the partial pressures of the gases being delivered. Because the oxygen partial pressure is life critical in this development, the instability which derives from "pool boiling" must be completely avoided.

If a system is considered whereby a volume of liquid is removed unchanged from one container and then totally vaporized and mixed in a separate container, the percentages of individual gaseous components will of course be identical to the percentages of individual components in the liquid. Continuous total vaporization and mixing of liquid unchanged from the tank composition can be accomplished by withdrawing liquid through an orifice small enough so that a constant flow of liquid in one direction is obtained followed by total vaporization and turbulent mixing in a sufficiently long, small diameter, heat exchanger.

B. FLOW CONTROL

Since pressurization and venting of present day spacesuits require a flow rate of approximately 5.0 ACFM, a flow control mechanism is needed to regulate flow according to changes in diving depth. To maintain 5.0 ACFM through the suit will require a gaseous flow rate which can be increased as depth increases. At a water depth of 40 feet (MSFC Neutral Buoyancy Tank depth), a flow rate of 10.9 SCFM is needed to yield a 5.0 ACFM flow rate through the suit.

Regulating the amount of liquid cryogen which can enter the heat exchanger can be used to regulate the output gas rate. The heat exchanger is allowed to operate at low pressure and only the amount of liquid required to give a selected flow rate enters the heat exchanger. The rate this liquid enters can be controlled by controlling the orifice and dewar pressure. Since a small volume of liquid will yield a large volume of gas, optimum flow control and PO_2 control can be obtained by using a small orifice, variable flow, control valve which meters liquid only. Therefore, the flow control valve can satisfy the flow control requirement discussed above and also the oxygen control requirement discussed in Section A.

C. TEMPERATURE CONTROL

The established comfort level for neutral buoyancy pressure suited subjects has been found to vary between 68°F and 80°F. The heat exchanger on Prototype II is overdesigned with respect to its heat exchange capacity so that extremely large flow rates can be accommodated without any appreciable drop in output temperature below ambient water temperature. Since the Prototype II unit was designed for underwater purposes, a heat exchanger suitable for an air environment was not considered.

D. STORAGE CONTAINER

The best available insulation would be a vacuum walled container possibly including multilayered "superinsulation". This type insulation would restrict heat loss to an insignificant value during the required one hour run time. The only significant operational contribution of vacuum insulation would be its extended "holding time" (16 to 20 hours might be expected). However, vacuum based insulation techniques have three distinct disadvantages: (1) cost, (2) fragility, and (3) heavy walls required as over pressure (depth) increases.

Preliminary calculations on other methods of insulation indicated that polyurethane foamed-in-place insulation would be inexpensive, lighter in weight, and more rugged than vacuum insulation. The only disadvantage of foamed polyurethane appeared to be a reduction of the dewar holding time to about three to five hours; this was considered adequate. Further, since neutral buoyancy simulation is a centralized operation, the combination of a standard high vacuum ambient pressure storage dewar plus the foam insulated diving dewar would allow a cryogen holding time of several days plus sufficient insulation for mission performance.

FINAL PROTOTYPE DESIGN

The final prototype design, known as Prototype IIA, is shown in Figure 2 and Figure 3. The unit can be loaded in a few minutes using a premix of the desired ratio of liquid oxygen and liquid nitrogen. For operation the vent valve is closed and the buildup valve is opened. Cryogenic tank pressure is built up and controlled by the build up circuit. The diver simply sets the flow control valve and plugs in to the outlet to obtained controlled delivery.

EXPERIMENTAL EVALUATION

A. TEST EQUIPMENT

In order to measure pertinent characteristics of the gas being discharged form the life support system an instrumented "analysis bar" (see Figure 4) was used in place of the pressure suited test subject. This analysis bar contained sensors for measuring the following parameters: (1) oxygen partial pressure, (2) system absolute pressure (3) actual flow rate output, and (4) output gas temperature.

Analog signals representative of these parameters were fed into a recorder so that all values could be recorded simultaneously on chart paper for future reference.

B. TEST TECHNIQUES

Preliminary testing of the unit was accomplished under standard atmospheric (ambient) conditions substituting liquid nitrogen for LOX/LN_2 (LON) mixtures. This phase of testing not only afforded the opportunity for gaining operational familiarity, but also permitted reliability testing of key components, valves and heat exchanger. Changes in the location of these components and changes in their operating conditions were made as dictated by the test results.

After establishing the operating reliability of the unit, tests were conducted using mixtures of LOX and LN_2 as the filling liquid. These tests, consuming over 2000 lbs. of cryogen, were conducted to establish PO_2 control and to determine any changes in PO_2 which may occur during filling. A performance chart for a typical run using LON is shown in Figure 5. Strip chart data for another run are given in the Appendix.

In addition to the standard 1-atmosphere tests, testing was also conducted at smiulated diving depths up to 100 feet in the single chamber recompression facility located at MSFC. These tests were conducted to establish the effects of increased ambient pressure on PO_2, flow rates, output temperature, and the structural integrity of the unit. A performance chart for a typical simulated dive to 80 feet is shown in Figure 6. Strip chart data recordings for a dive to 50 ft. are given in the Appendix.

C. TEST RESULTS

Actual testing of the Prototype unit yielded the following results:

1. The basic cryogenic-gas cycle used by the Prototype II Unit provides reliable control of all parameters.

2. The special valve components of this cycle (pressure closing valve, relief valve and micrometer flow control valve) perform adequately and reliably under normal and special conditions including being submerged to a depth of 100 ft.

The build up valve provides for complete internal system pressurization within 6 minutes as shown by Figure 7. The build up circuit will hold the desired dewar pressure within 2% under normal flow conditions and within 10% of preset pressure under continuous maximum flow conditions. The pressure closing valve operates automatically to compensate for depth overpressure and will maintain pre-set dewar pressures over ambient pressure at depths up to 100 feet.

Figure 8 shows the performance of the micrometer flow control valve. This valve is linear and smooth under all conditions of cryogen flow required and can provide the flow control and orifice necessary for PO_2 control. Flow rates from 1 through 18.5 SCFM are possible at 80 or 125 psi dewar pressure.

Flow in SCFM from the Prototype II unit is dependent only on dewar ambient pressure and flow control valve setting. Testing showed that the pressure closing valve accurately maintained the preset differential pressure above ambient pressure. Consequently, flowrates (in SCFM) were found to be maintained at constant values dependent only on the flow control valve setting. Figure 9 shows for the Prototype II unit the relation between flowrates (in ACFM) and water depth for a given setting of the flow control valve. However, constancy of flow rate in SCFM is in basic contradiction to the requirements of a pressure-suited neutral buoyancy test subject; his situation demands that flowrate through the suit in ACFM be constant and that SCFM be adjusted with respect to depth to accommodate this requirement. Thus an important design feature of the Prototype II unit is a dive adjustable flowrate control which provides more than adequate gaseous flow levels under all neutral buoyancy depth-demand conditions.

3. The Prototype II unit will convert and deliver the oxygen content with high precision control as observed during

all LON testing (which included more than 2000 pounds of various LON mixtures).

Total PO_2 control includes accuracy of LON mixing, changes of LON ratio during storage, changes of LON ratio during dewar transfers (loading), and any change which might occur during operation. It is interesting to note that during the entire test program these cumulative factors never caused a PO_2 variation in excess of + 5%. If one considers a given run cycle only, eliminating the inaccuracies of mixing, storage and loading, PO_2 variation is reduced to less than ± 1/2% (which approaches the accuracy limit of the PO_2 sensor).

Figure 10 represents total PO_2 variation for typical $LO_{20}N_{80}$ and $LO_{30}N_{70}$ mixtures for surface conditions.

The PO_2 depth control was also in excellent agreement with theoretical and precomputed values. In a constant ratio mixture such as gaseous air or liquid air ($LO_{20}N_{80}$) or any other specific liquid oxygen/nitrogen (LON) ratio mixture, hyperbaric operation will of course show PO_2 changes. The oxygen constituent must always contribute its relative fraction of the total hyperbaric pressure. Therefore as the ambient pressure is elevated on a constant ratio mixture the oxygen partial pressure must also be proportionately elevated.

Figure 11 shows a typical depth vs PO_2 performace curve for the Prototype II Unit. Two typical LON ratios are shown. The actual PO_2 depth curves are as linear and flat as the PO_2 curves obtained from an air dive (deviations are less than 0.1%). The PO_2 agreement with respect to precomputed values is also very good. The actual PO_2 curve in Figure 11 in all cases showed a slightly lower slope than the precomputed values. This type deviation is typical of all air dives and is felt to be due to a slight lag in the electrochemical PO_2 sensor from which all the PO_2 values were obtained.

Although PO_2 will vary with depth, this variance is in accordance with Dalton's Law and is exactly the same as for an air dive. The maximum PO_2 from any LON mixture used at any depth can be predicted and the Prototype II will deliver that value. For instance, in a $LO_{33}N_{67}$ mix, an oxygen partial pressure of 0.33 atmosphere (4.85 psia or 251 mm Hg) will be found at the surface, whereas this same mixture will show a PO_2 of 0.65 atmosphere at a depth of 40 feet.

4. Testing has shown that the Prototype II Unit will deliver positive, safe output gas temperatures under all submerged conditions down to depths of at least 60 feet. The

principle of an overdesigned heat exchanger effectively locks the output gas temperature so that it is always within 5°F of the water temperature in which the unit is immersed. Figures 5 and 6 show the output gas temperature and the water temperature vs. time and depth respectively. These curves show a slight decline in both the output gas temperature and water bath temperature. This is due only to the limited volume of water surrounding the unit and would not occur if the unit were operated in a large volume of water such as the neutral buoyancy tank.

The unit can be operated at 5.0 SCFM at surface ambient conditions (heat exchanger in air) only 5 minutes before the output gas temperature begins to drop. No attempt was made to size the heat exchanger or to provide auxillary heat control for such ambient air operations.

The heat exchanger operated as expected under all conditions down to depths of 60 ft. and showed sensible cooling in the first few feet of exchanger length. This cooling did not produce ice at depths less than 60 feet. Ice was produced on the first few coils only when maximum flow rates were demanded at depths below 60 feet. This ice formation is due to the increased dwell time of the gas inside the heat exchanger as gas density is increased. Ice formation was never found to include a supercooled surface. Bare skin contact with an immersed and icing heat exchanger showed no tendency for skin adherence.

Thus, in actual testing, the heat exchanger design described here proved to be completely free of potential physiological hazards associated with low temperatures, cold gas or supercooled surfaces, at least for the pressures and flow rates of interest.

CONCLUSIONS

The MSFC Prototype II Cryogenic Life Support System will provide adequate gas for present neutral buoyancy operations. Flow is diver adjustable for comfort. Positive oxygen partial pressure control is inherent within the design and the performance of the unit with respect to oxygen partial pressures is exactly analagous to an air dive. The unit will deliver exactly that ratio of gas contained in the liquid phase in the tank. Selection of oxygen/nitrogen ratios other than air may be desirable and are easily possible with this system. Positive output gas temperature control is also inherent within the Prototype II design. During submerged operation, the output gas temperature is fixed directly by the water temperature. Even under the highest flow conditions the gas temperature will not be more than a few degrees below water temperature.

This unit is being refined to include more efficient layout and packaging and to include the all-attitude dewar solution. It will then be put through man rating qualification tests for use within the MSFC neutral buoyancy facility.

Credits

The authors wish to thank Mr. W. D. Hand of the Hayes International Corporation and Mr. J D Bennight of Marshall Space Flight Center for their continued support and aid in accomplishing this project.

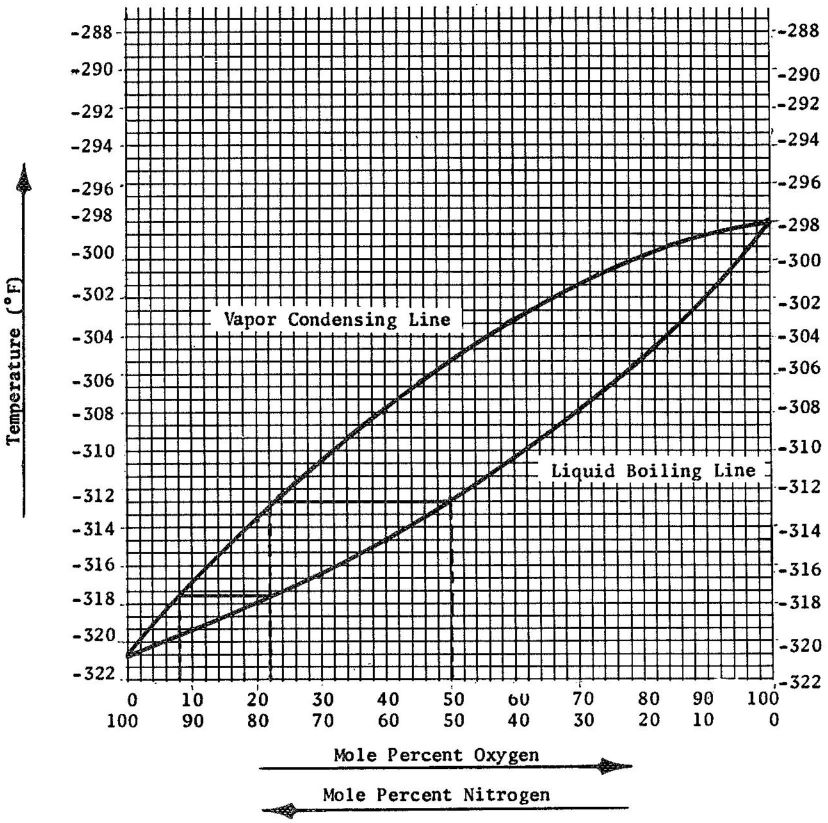


Figure 1. EQUILIBRIUM DIAGRAM FOR LIQUID OXYGEN-LIQUID NITROGEN MIXTURES

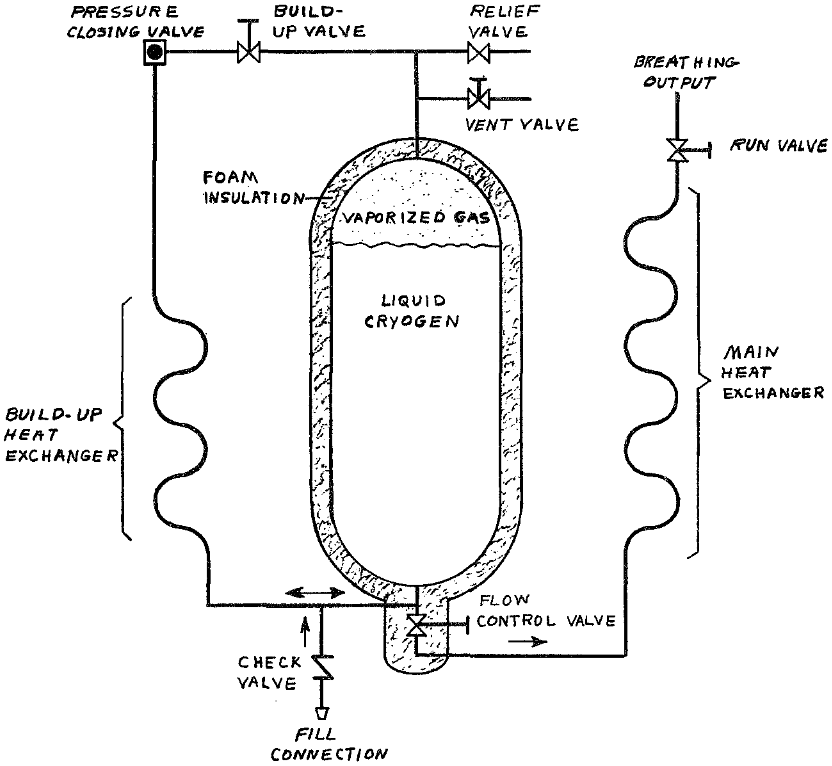


Figure 2. SCHEMATIC OF MSFC PROTOTYPE II UNDERWATER LIFE SUPPORT UNIT.

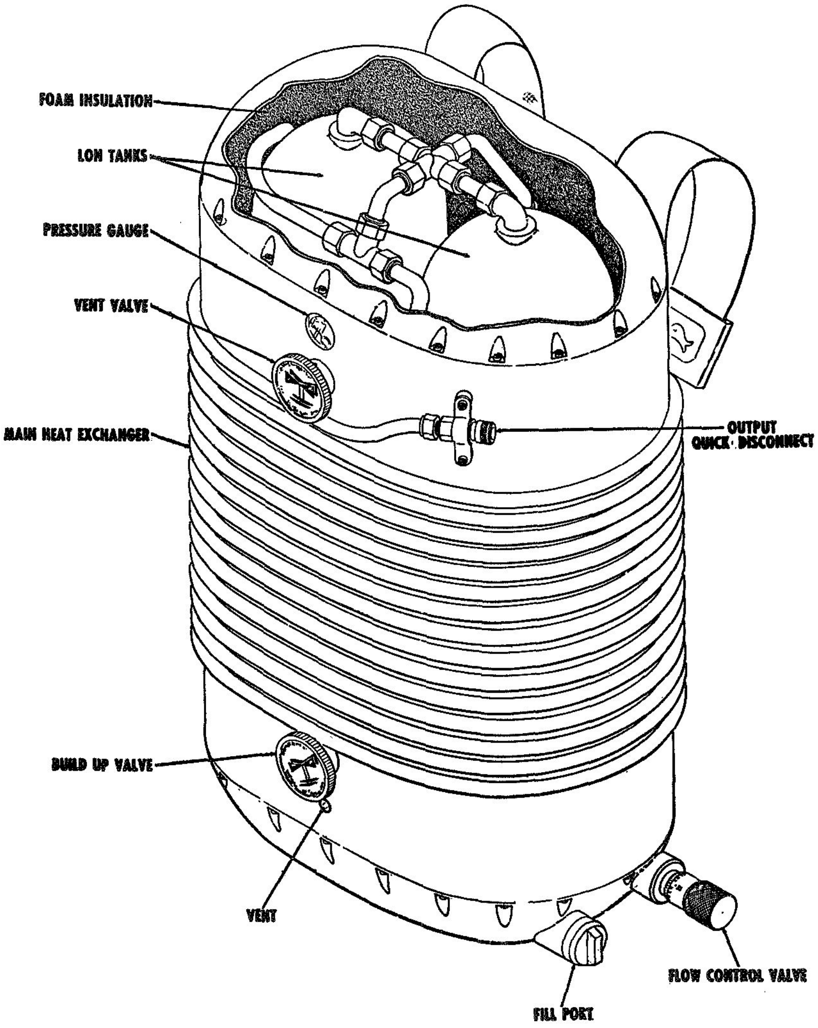


Figure 3. Prototype IIA Cryogenic Underwater Life Support System

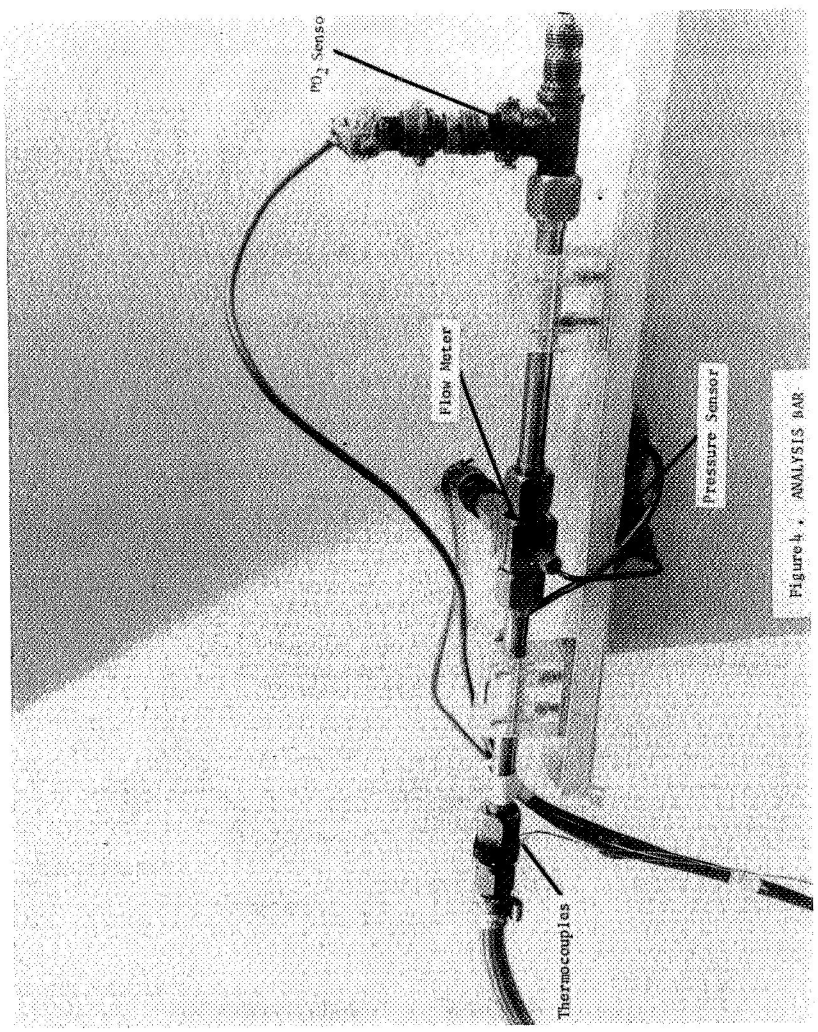


Figure 4. ANALYSIS BAR

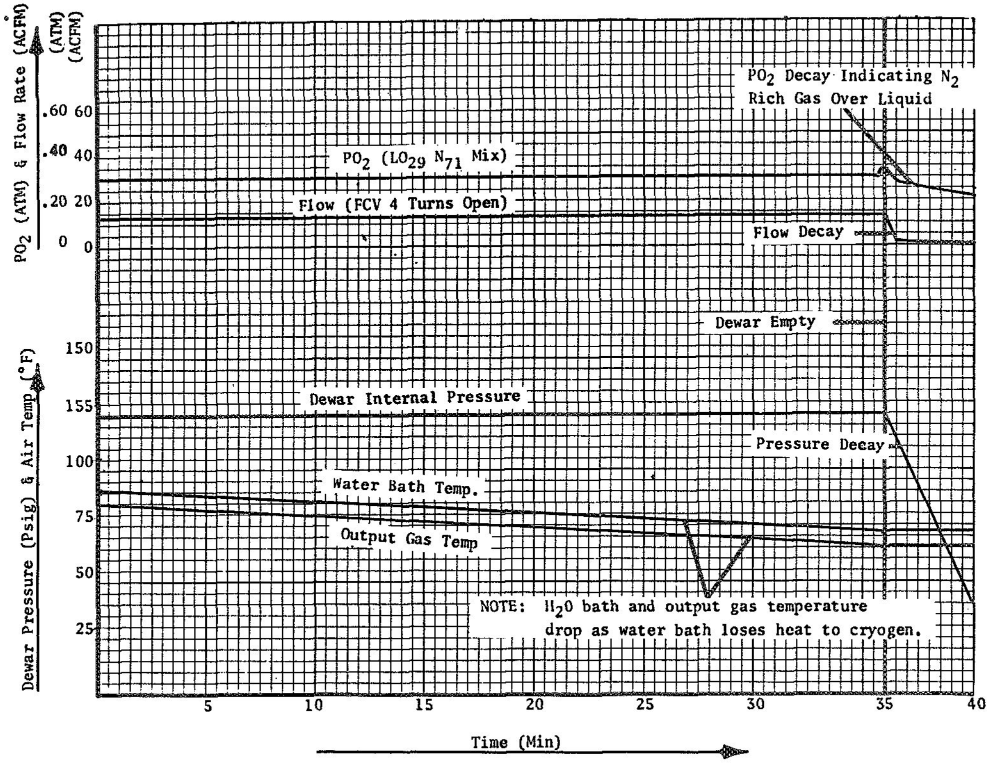


Figure 5. MSFC PROTOTYPE II PERFORMANCE CHART (SURFACE CONDITIONS)

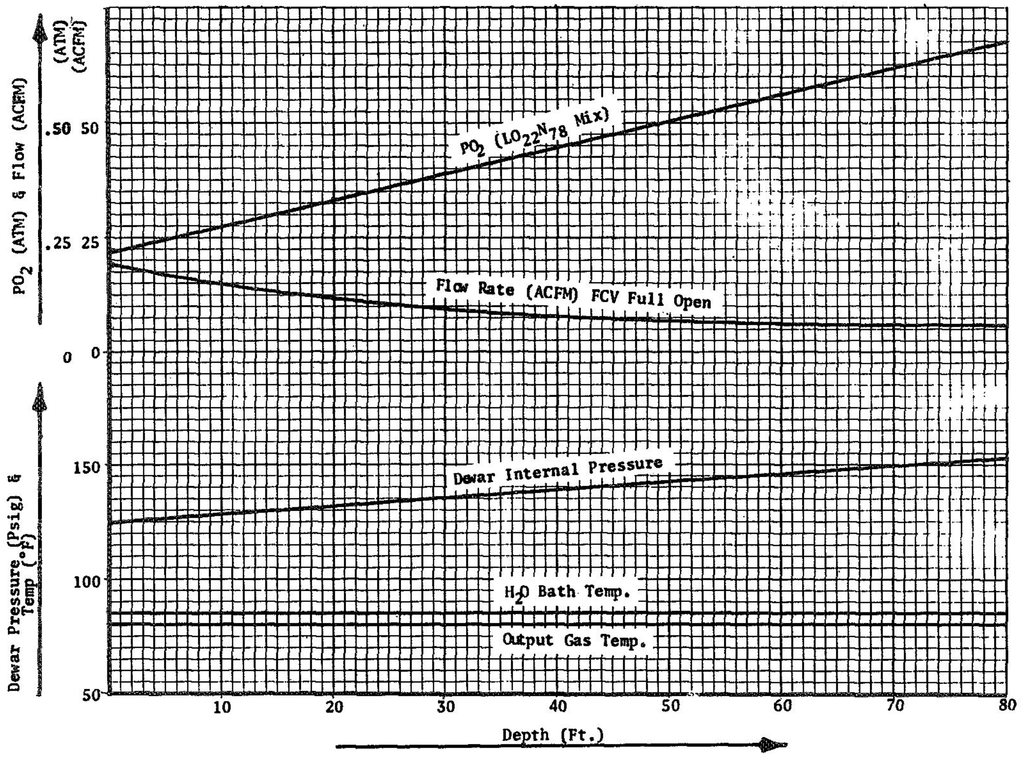


Figure 6. MSFC PROTOTYPE II PERFORMANCE CHART (DIVE CONDITIONS)

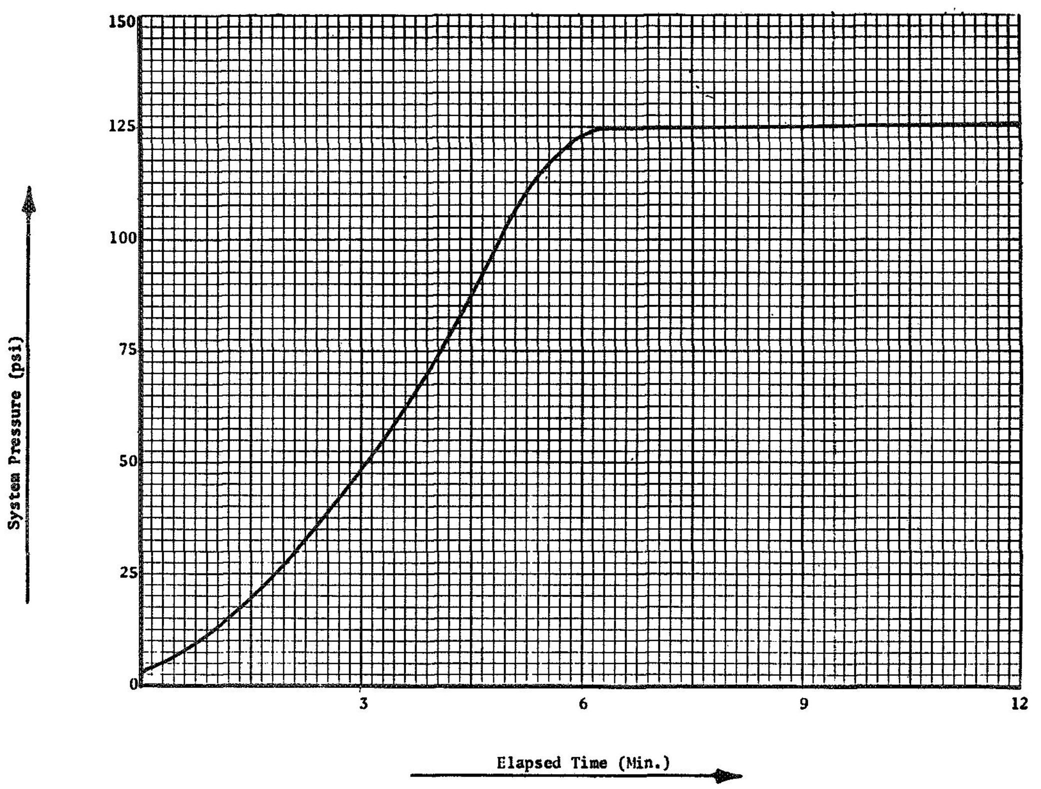


Figure 7. PRESSURE BUILD UP CURVE FOR PROTOTYPE II UNIT

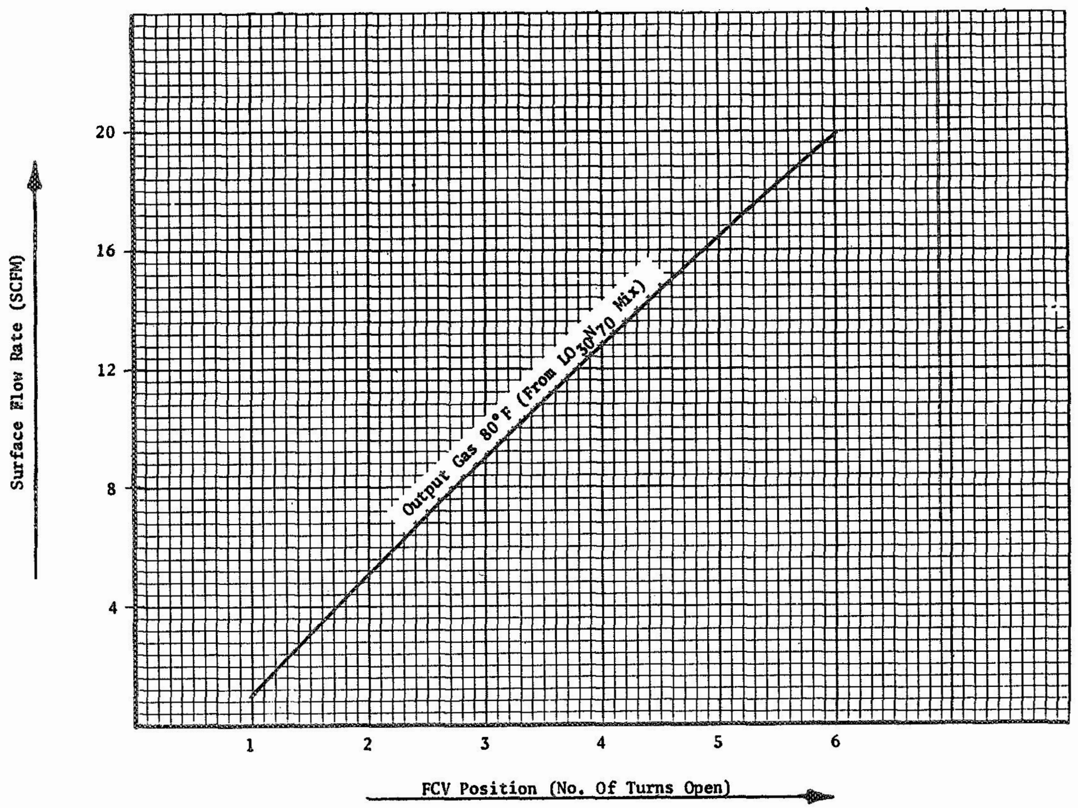


Figure 8. FLOW RATE VS. FLOW CONTROL VALVE POSITION (MSFC PROTOTYPE II UNIT)

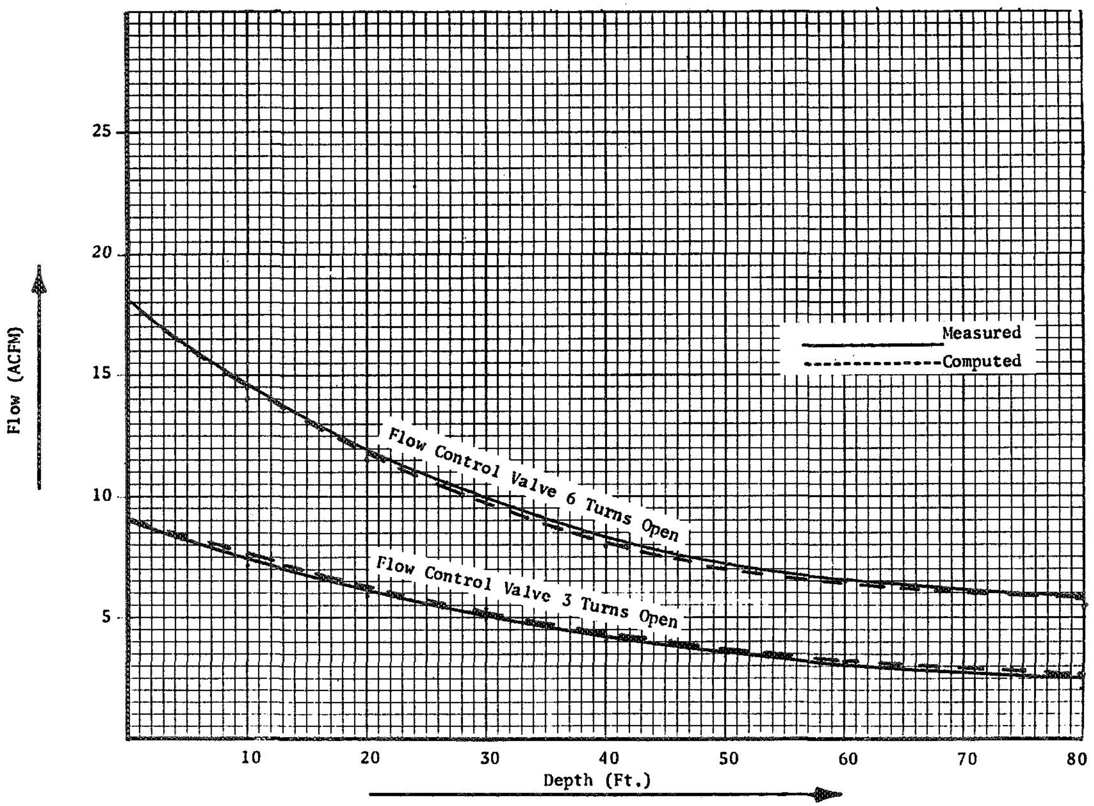


Figure 9 . FLOW RATE VS. DEPTH

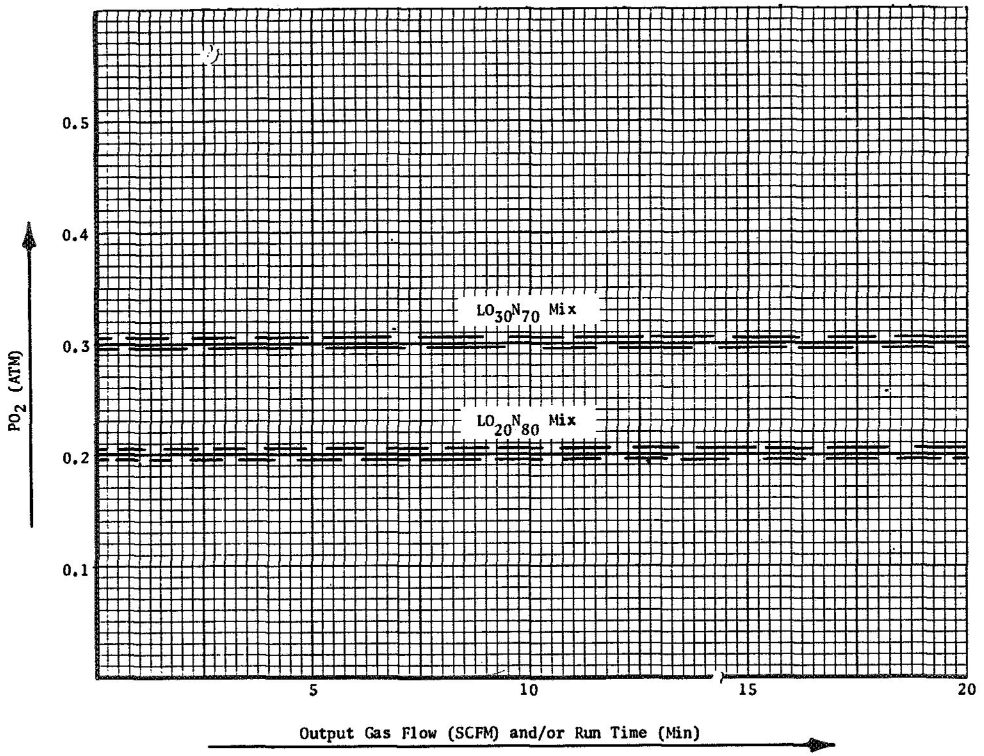


Figure 10. OUTPUT GAS ANALYSIS VS. FLOW RATE AND RUN TIME

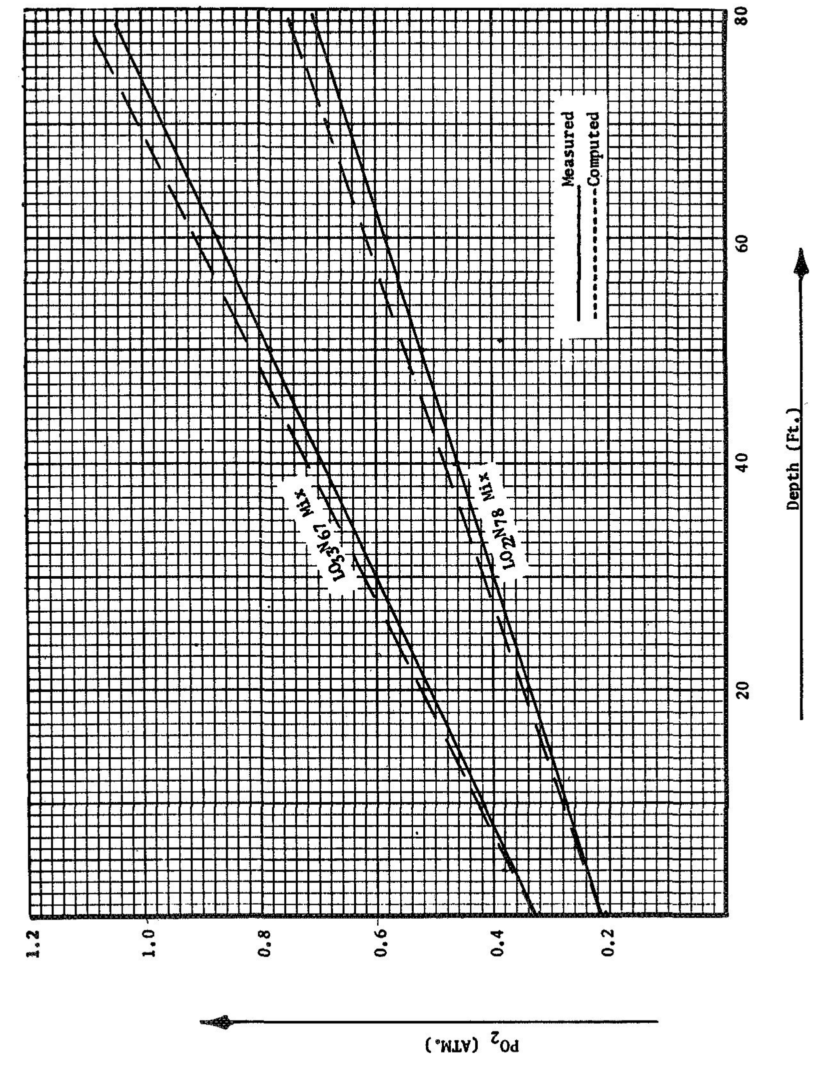
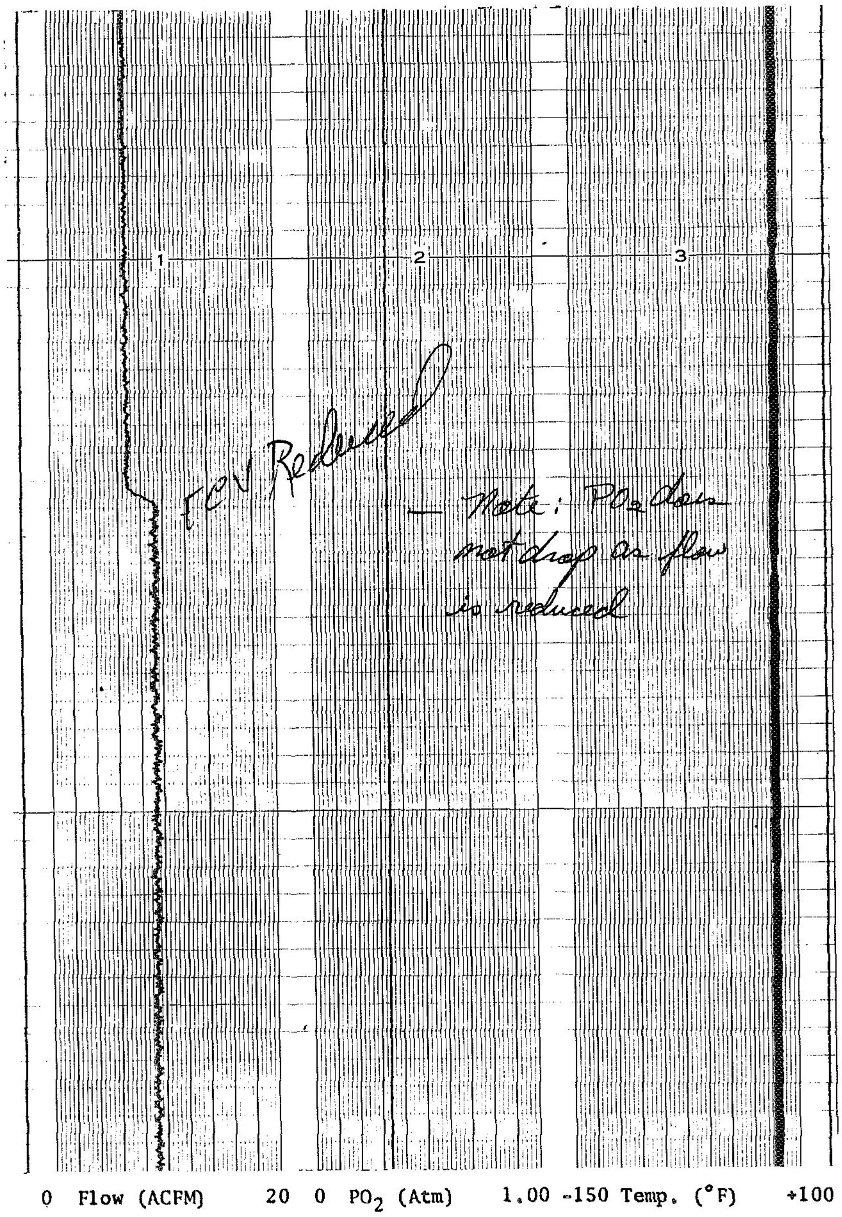
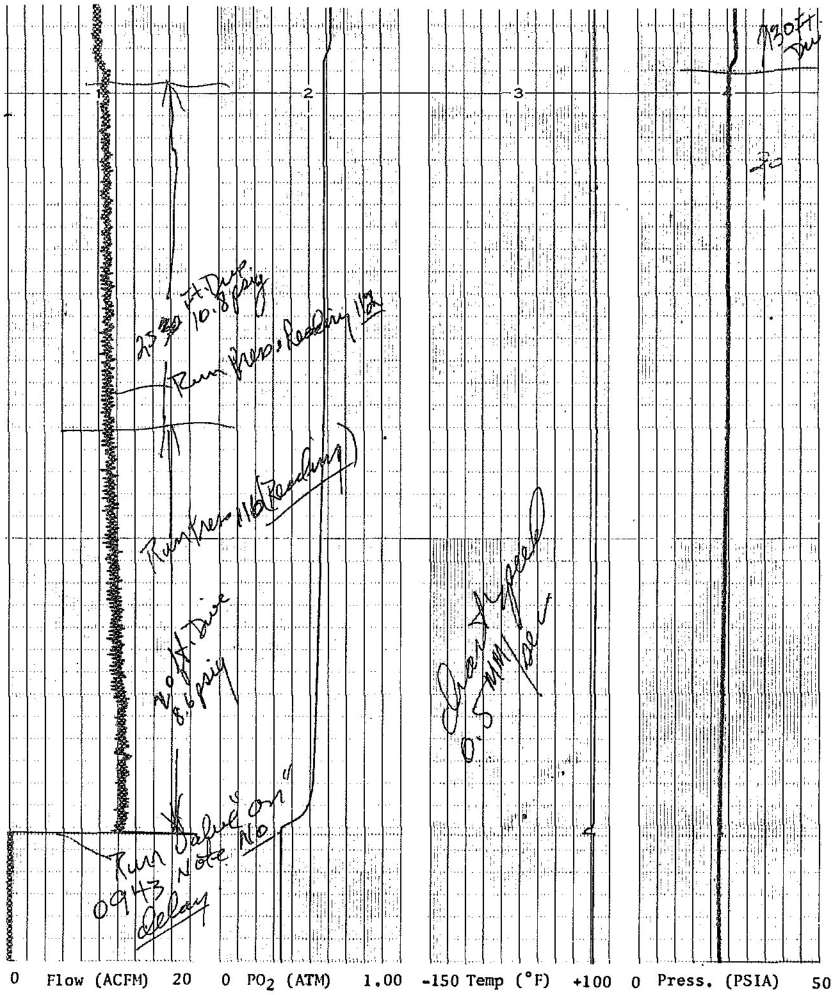


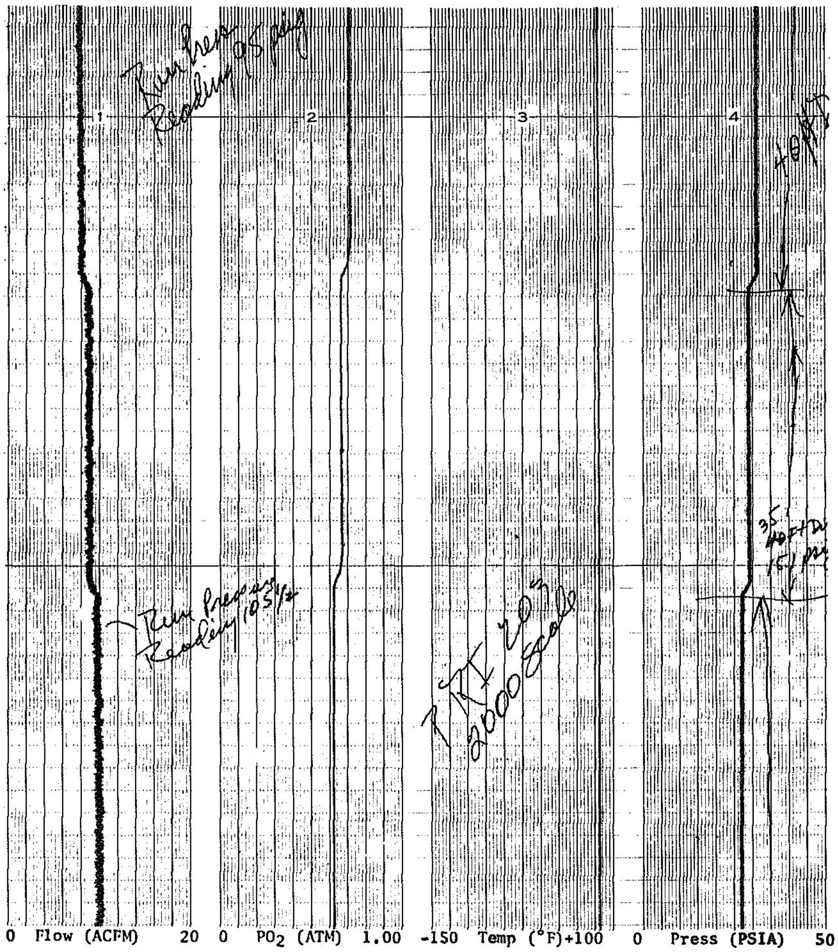
Figure 11. PO2 VS. DEPTH (MSFC PROTOTYPE II UNIT)



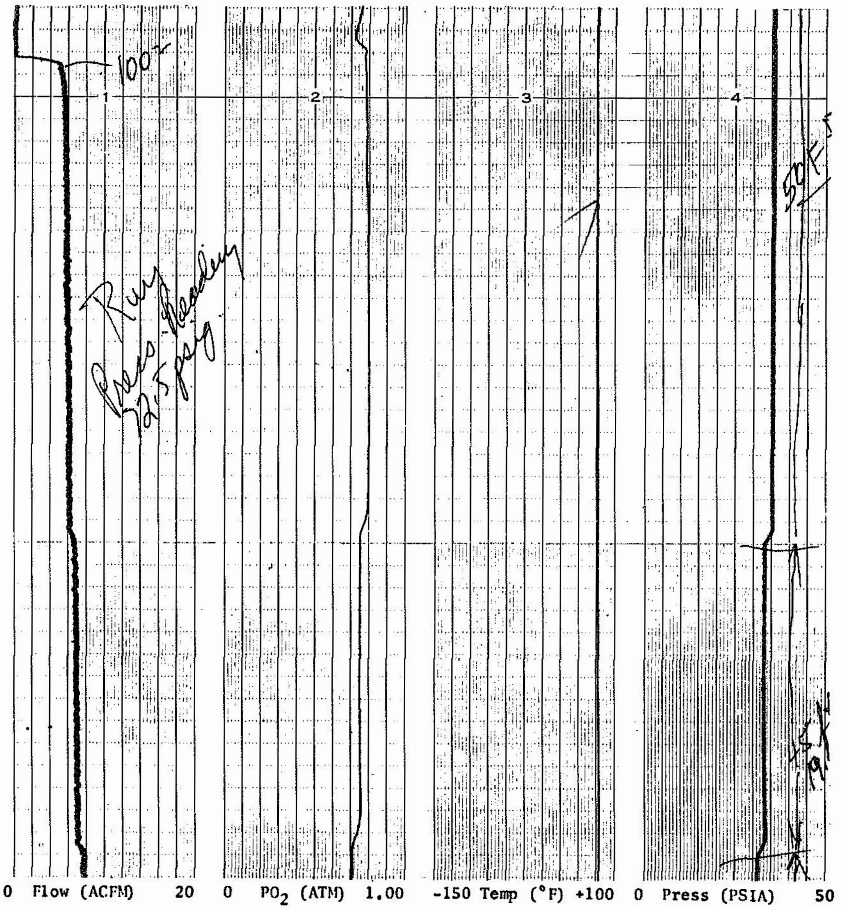
Strip Chart Data For MSFC Prototype II Life Support Unit. (Surface Conditions)



Strip Chart Data For MSFC Prototype
Underwater Life Support Unit
(Dive Conditions, 25 Sept. 1969, Run #1, 24 Sept.
LON Mix, Initial Water Temp 87°F)



Run #1 24 Sept. 1969 Continued



Run #1, 24 Sept. 1969 (Continued from previous page).