N72-27116

10

SEMICLOSED-CIRCUIT ATMOSPHERE CONTROL IN A PORTABLE RECOMPRESSION CHAMBER*

Peter S. Riegel and Don W. Caudy
BATTELLE
Columbus Laboratories

INTRODUCTION

One of the better known hazards of diving is decompression sickness, or "the bends." As the diver goes deeper, his respiratory system and bloodstream are exposed to increased pressures of the gas he is breathing, commonly oxygen, helium, and nitrogen. In dives of extended duration, these gases become dissolved in his tissues. As the diver ascends gradually, the excess nitrogen or helium escapes through the lungs, while the oxygen is absorbed by the body. Rapid ascent may allow the inert gases to form bubbles in the tissues and bloodstream, blocking circulation and causing tissues to swell.

The probability of bubble formation increases with depth and duration of the dive and the speed of ascent. The severity of effect depends on the area of the body where the bubbles are formed. Pain, dizziness, respiratory difficulty, nervous disorders, or death may result.

Another serious hazard to the diver is air embolism. If a diver should unwittingly hold his breath during ascent, the expanding gas may overinflate his lungs, causing leakage of air bubbles into his chest cavity or bloodstream and possibly lead to blockage of blood vessels in the heart or brain. Convulsion, brain damage, or death may result.

Since these afflictions are consequences of gas bubbles in the diver's body, treatment is directed at removing the bubbles or reducing their size. This is commonly done by recompressing the diver in a chamber that reduces bubble size and promotes rediffusion of the gas into the tissues and bloodstream. Once relief of symptoms is reached, decompression may begin at a low rate to prevent recurrence of decompression sickness.

The main drawback to recompression treatment is that a pressure chamber is required, and generally it is not located at the site of the diving accident. Often a semiconscious, suffering man must be transported by the fastest means to reach the nearest recompression facility, with the probability of permanent damage increasing with every minute he remains untreated.

To provide means of protecting divers in remote worksites, some small, portable recompression chambers have been developed and marketed. These chambers are of various forms: some are cylindrical, some tapered, some telescoping. Entry may be head first or feet first. All chambers of this type are sized for one man and are intended to give immediate treatment to the sufferer, wherever he may be. Once the patient is under pressure, the chamber may be transported to the nearest recompression facility for subsequent treatment of the occupant. During transportation, the atmosphere in the chamber is kept pure by continuous ventilation with air, which supplies oxygen and removes unwanted carbon dioxide. During ventilation large flows of air are required to dilute and remove chamber carbon dioxide, but little of the oxygen content is used.

---

*Chamber development is being funded through Office of Naval Research Contract No. N00014-70-C-0072.

Because of the overlap among the fields of mechanical engineering, medicine, and air conditioning, units familiar to workers in those areas are used here. For example, pressure is expressed in feet of seawater, atmospheres absolute (ATA), lb/sq in., lb/sq ft, and in. of water, depending on the area of use. Man consumes and produces gasses at rates measured in standard liters per minute (SLPM) by medical people.

Gas flows, measured at standard conditions (essentially at atmospheric pressure, and at 0°, 68°, or 70° F, depending on the standard employed) are preceded by an "S"; if measured at flowing conditions, flows are preceded by an "A"–for example, at 6 ATA pressure, 1 ACFM = 6 SCFM.

A typical chamber occupant will consume about 0.24 SLPM oxygen and produce 0.20 SLPM carbon dioxide. Partial pressure of carbon dioxide could be maintained at less than 0.005 ATA, a safe level, by ventilation at a rate of 2 ACFM. However, to produce a flow of 2 ACFM at a typical treatment depth of 165 ft requires a flow of 12 SCFM of air. A typical commercial air flask contains about 240 cu ft, or enough for less than 20 min operation. Efficient treatment and transportation would require that enough of these heavy, cumbersome bottles accompany the chamber to provide air for the entire duration of the trip. In some cases, this is difficult or impossible, either through weight or size limitations of the carrier, or because not enough air is available.

The problem of efficient gas usage has been effectively solved in diving apparatus through use of recirculation systems, such as semiclosed-circuit and closed-circuit rebreathers. The same principles can be applied to operation of a recompression chamber.

In keeping with the need for a simple, foolproof system, the use of the oxygen sensors, batteries, and associated electronic circuits used in closed-circuit systems was rejected. To be effective, the system must be capable of surviving a long storage time and be quickly ready for use in remote locations with a readily obtained gas supply. Air was chosen as the ventilation gas because of its availability and suitable oxygen content. A semiclosed-circuit ventilation system offers the utmost in simplicity, reliability, and conservation of gas supply. Gas is admitted and circulated with little complexity, and maintenance and upkeep requirements are minimal.

DESIGN PHILOSOPHY

In creating a life support system, a consistent philosophy of design is necessary to keep unnecessary superfluities from creeping in as well as to assure that all necessary functions are present. The function of the chamber is to permit rapid insertion and recompression of an injured diver, and transportation to a suitable treatment facility where he can be removed to a larger chamber and treated by medical personnel.

Lightweight construction is important, as the system will sometimes have to be moved by hand. Compactness is desirable so that the system may be loaded into varied forms of transport. The equipment should require a minimum of operator training (instruction should be possible within a few minutes) and operation should be simple. Ability to perform well after long storage periods is desirable. Reliance on external power systems should be avoided for they may not be available in the field.

The system as designed carries no frills. It is simply a container for an injured man, and preservation of his life is the only consideration. Discomfort should certainly be avoided, but so should complexity. In our approach, we have tried to keep the system pared down to the minimum required to do the job effectively.

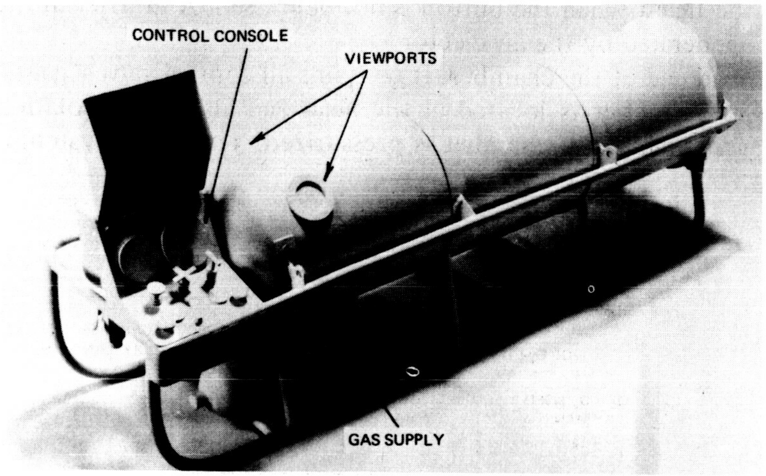

Figure 10.1 *Model of recompression chamber, front side.*

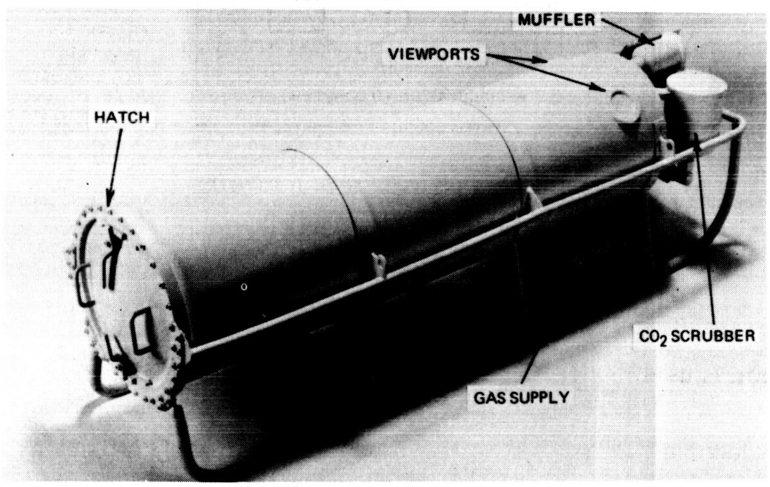

Figure 10.2 *Model of recompression chamber, back side.*

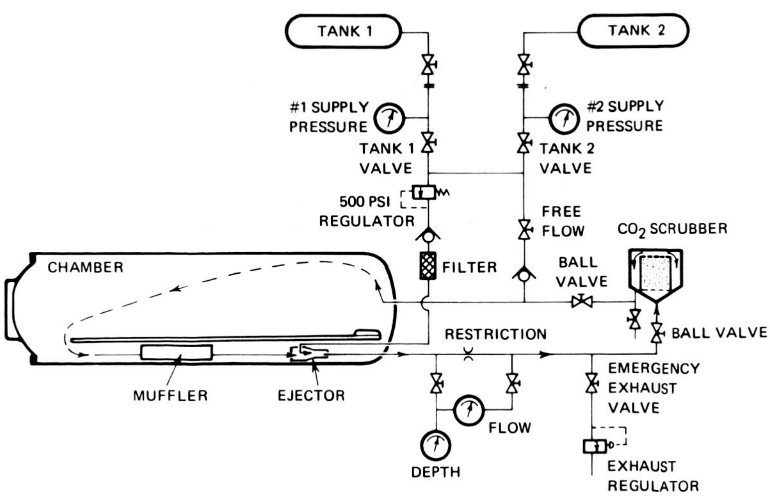

Figure 10.3 *System schematic.*

CHAMBER DESCRIPTION

The portable recompression chamber and its associated equipment is shown in model form in figures 10.1 and 10.2, and schematically in figure 10.3. The pressure shell is made of 5/32-in. rolled and welded 5083 aluminum with a semielliptical self-energizing hatch. The basic shape is a 22-in-diam cylinder with an inside length of about 84 in. Total system volume, including piping and canister, is about 18.3 cu ft. Pressure capability permits treatment to depths of 165 ft of seawater (6 ATA). Two 4-in. viewports permit observation of the patient.

To enter the chamber, the patient is placed on a stretcher, strapped down, and slid in head first. The hatch is closed and dogged, and the system is ready for pressurization. Water and food containers are placed within the patient's reach to keep him supplied for the duration of his stay. No medical lock is provided.

The chamber may be operated in two modes—open circuit or semiclosed circuit. In locations where either a large compressed air supply in tanks or a suitable compressor is available, open-circuit operation will be employed. During transportation and in places where limited compressed air in tanks is available, semiclosed-circuit operation will be used.

A chamber communications system permits two-way conversation between patient and attendant. The attendant must push a button to talk; the patient can be heard when the button is not depressed. A muffler in the gas circulation system silences the noise generated by the air ejector.

A control console is located at the head end of the chamber. It contains all control valves, gages, and communications equipment. The gas scrubber is located at the head end also, with isolation valves provided to permit changing reagents while the chamber is pressurized. The entire system is mounted on skids to facilitate handling.

Total system weight is 330 lb.

SYSTEM ANALYSIS

Ventilation requirements were determined by means of a system analysis as follows (fig. 10.4). Note that the man is shown outside the system boundary. In fact, he is inside, of course, but in this analysis he serves only as a sink that removes oxygen from the system and adds carbon dioxide to the system. Similarly, the carbon dioxide absorber, although enclosed in the actual system, serves as a sink that removes carbon dioxide from the theoretical system.

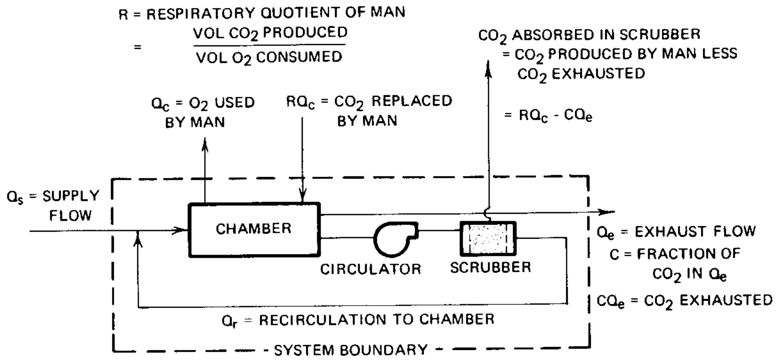

Figure 10.4 *Simplified system for analysis.*

In this discussion, the following notation is used.

t = time, min.
X = percent oxygen in chamber, decimal
X_o = value of X at $t = 0$
C = percent carbon dioxide in chamber, decimal
Q_s = supply flow, SCFM
Q_e = exhaust flow, SCFM
Q_c = rate of oxygen consumption, SCFM, typically Q_3 = 0.24 SLPM = 0.0085 SCFM for man resting
Q_r = recirculation flow, SCFM
G = percent oxygen in supply gas (G = 0.21 for air)
R = respiratory quotient, ratio carbon dioxide produced to oxygen consumed by occupant, typically R = 0.8 for man resting
P = chamber pressure, ATA
V = chamber volume, cu ft

An oxygen balance of the semiclosed-circuit recompression chamber comprises

System oxygen content, cu ft	$= PVX$
Oxygen flowing into system, SCFM	$= Q_sG$
Oxygen consumed by man, SCFM	$= Q_c$
Oxygen exhausted from systems, SCFM	$= Q_eX$

The rate of change of system oxygen content may be described by

$$\frac{d}{dt}(PVX) = Q_sG - Q_eX - Q_c \tag{1}$$

or, since P and V are constant at a given depth,

$$\frac{dX}{dt} + \left(\frac{Q_e}{PV}\right) X = \frac{Q_sG - Q_c}{PV} \tag{2}$$

Equation (2) may be solved by conventional methods, and after substitution of boundary conditions will yield

$$X = \underbrace{\left(X_o - \frac{B}{A}\right) e^{-At}}_{\text{transient}} + \underbrace{\frac{B}{A}}_{\text{steady state}} \tag{3}$$

where

$$A = \frac{Q_e}{PV} \tag{4}$$

$$B = \frac{Q_sG - Q_c}{PV} \tag{5}$$

Equation (3) will be useful, but not until the value of the exhaust flow Q_e, which is part of constant "A," is found.

To determine the value of Q_e, a total system flow balance must be taken. Since P is constant, the sum of all th~~e flows entering a~~nd leaving the system will be zero, or

$$\begin{matrix}\text{Supply} \\ \text{flow}\end{matrix} - \begin{matrix}O_2 \text{ used} \\ \text{by man}\end{matrix} + \begin{matrix}CO_2 \text{ produced} \\ \text{by man}\end{matrix} - \begin{matrix}\text{Gas} \\ \text{exhausted}\end{matrix} - \begin{matrix}CO_2 \text{ absorbed} \\ \text{in scrubber}\end{matrix} = 0$$

or

$$Q_s - Q_c + RQ_c - Q_e - \left(RQ_c - CQ_e\right) = 0 \tag{6}$$

or

$$Q_e = \frac{Q_s - Q_c}{1 - C} \tag{7}$$

The value of C must now be found. The total flow of carbon dioxide through the chamber is that produced by the diver. The total flow of gas is equal to that entering the chamber, less the oxygen consumed, plus the carbon dioxide produced by the diver. The value of C will be the ratio of these two flows, or

$$C = \frac{RQ_c}{Q_s + Q_r - Q_c\,(1 - R)} \tag{8}$$

If we now substitute equation (8) into (7) and (7) into (4), we obtain equation (3):

$$X = \underbrace{\left(X_o - \frac{B}{A}\right) e^{-At}}_{\text{transient}} + \underbrace{\frac{B}{A}}_{\text{steady state}}$$

where

$$A = \frac{Q_s - Q_c}{PV\,(1 - C)} \tag{9}$$

$$B = \frac{Q_sG - Q_c}{PV} \tag{10}$$

$$C = \frac{RQ_c}{Q_s + Q_r - Q_c\,(1 - R)} \tag{11}$$

Equations (3) and (8) represent exact solutions to the problems of oxygen and carbon dioxide concentration variation within the system. They may be simplified considerably for engineering use as outlined below.

For proper chamber ventilation, $Q_s + Q_r$, the ventilation rate, is far in excess of Q_c, the rate of oxygen uptake. Therefore, equation (8) may be simplified to

$$C \cong \frac{RQ_c}{Q_s + Q_r} \tag{12}$$

This is not exact, but it is accurate enough for most purposes.

Since C is normally quite low, less than 1 percent in a properly operating chamber, then $(1 - C) \cong 1$ and from equation (9),

$$A = \frac{Q_s - Q_c}{PV} \tag{13}$$

Since our primary interest lies in the steady-state solution to equation (3) the above simplification leads to

$$X_{\text{steady state}} = \frac{B}{A} \cong \frac{Q_s G - Q_c}{Q_s - Q_c} \tag{14}$$

The above expression is familiar to users of semiclosed scuba as one long used to calculate levels of breathing-bag oxygen.

The foregoing expressions for carbon dioxide and oxygen concentrations were used to prepare figure 10.5 and 10.6, which show the steady-state variation of the levels of these gases.

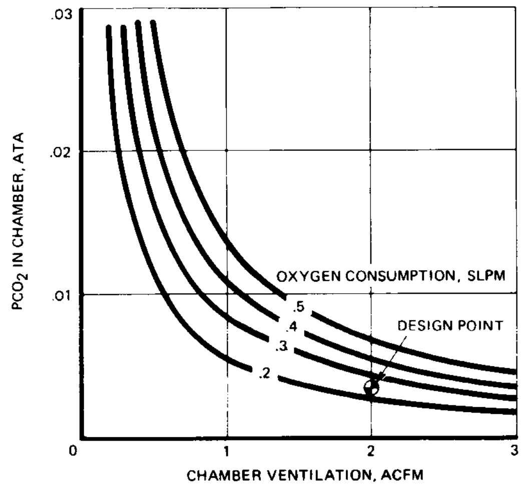

Figure 10.5 *Variation of* pCO_2 *with chamber ventilation.*

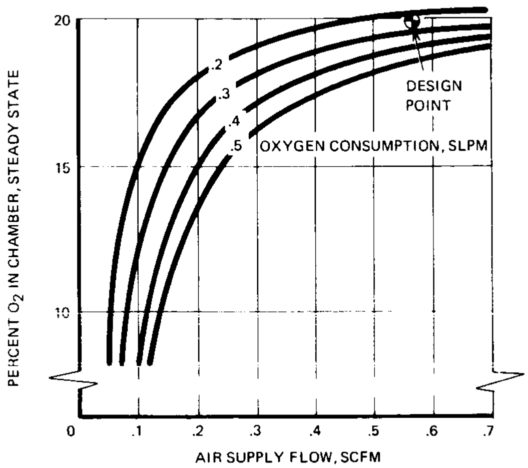

Figure 10.6 *Variation of percent* O_2 *with supply flow.*

DISCUSSION OF SYSTEM

Gas Circulation Methods

To remove the contaminants from the chamber atmosphere, it is necessary to circulate it through a scrubber and return it to the chamber. Some form of power is obviously required to operate the circulator. At the intended flow of 2 ACFM at depths to 165 ft, it was estimated that the pressure drop through the recirculation system would not be more than 4 in. of water. Three forms of power were considered—electric power, manpower, and gas power.

Because reliance on electrical power would require that batteries be charged and available at all times, and because this might not always be practical, it was considered that one of the other forms of power should be used, if possible.

Manpower, used to turn a crank or operate a treadmill, was not considered desirable because even at the low level of power required fatique could affect operation, and during transportation of the chamber it might not be possible to have the man accompany the chamber at all times unless the occupant was used as the source of power, which was quickly rejected. Besides, in the sort of emergency requiring the use of a recompression chamber, it would be a foolish waste of capability to use a man for such a simple task.

Gas power was considered an attractive alternative. Two approaches to gas power were apparent–an air motor to operate a circulating fan and an air ejector to circulate the atmosphere directly. The theoretical power required for circulating the gas was estimated to be on the order of 1/1000 hp. Even though dynamic shaft seals would have added to that, the power requirement was still far below the efficient capability of any commercial air motor. Although construction of such a motor was possible, its operating gas would have had to be wasted, since the necessary lubricants would contaminate the motor exhaust and make it unfit for breathing purposes.

Air Ejector

Use of an air ejector for circulation of the chamber atmosphere seemed very attractive, if feasible. The same air needed to replenish the chamber oxygen could be used to circulate the atmosphere. No batteries or moving parts were required. Ejectors have been used successfully for years on recirculating diving helmets, although not at the high flow ratios required on this chamber.

To determine the suitability of air ejectors, it was necessary to examine their characteristics and how they related to the gas supply requirements of the recompression system.

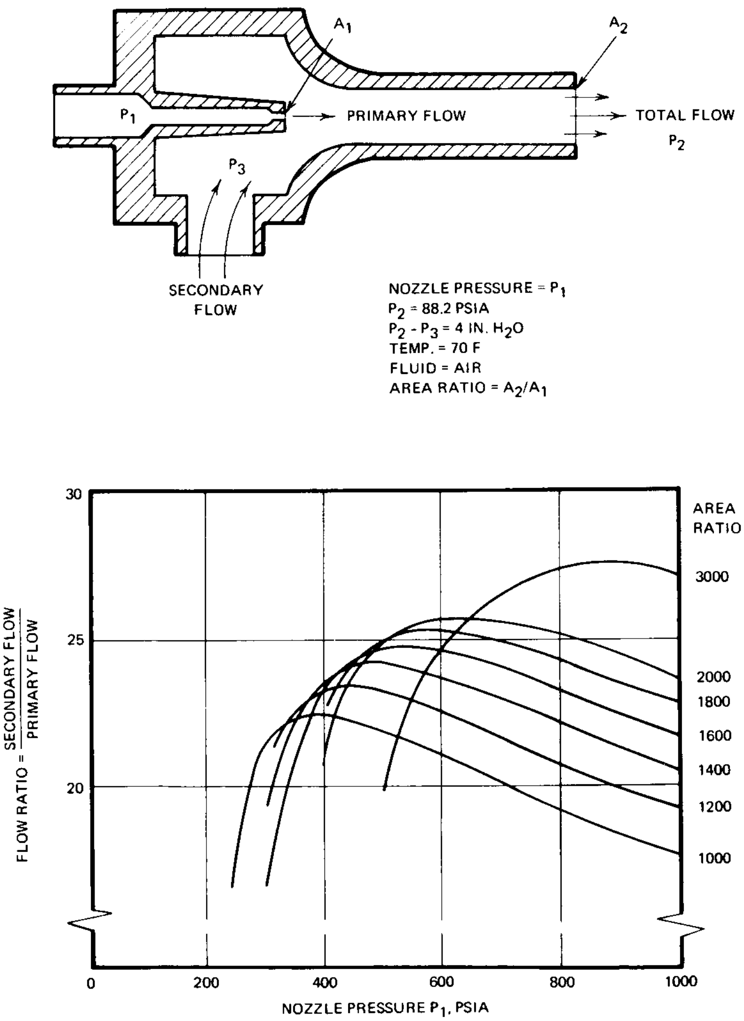

Figure 10.7 *Theoretical ejector characteristics.*

To estimate actual performance of an air ejector, the simultaneous solution of equations relating conservation of mass, energy, and momentum is required. Because there are many system variables, and because the solution is an iterative one, computer programs were written to aid in the computation. The results of the computation are shown in figure 10.7. In explanation of figure 10.7, the primary flow is that flow of gas which generates the circulation through the ejector. It is introduced through a high-pressure nozzle. The secondary flow is that flow induced in the chamber by the action of the ejector. Downstream pressure of 88.2 psia corresponds to the operating pressure of 165 ft of seawater. A pressure drop of 4 in water was estimated as the maximum that would be obtained through line friction in the system piping at the desired flow of 2 ACFM.

From figure 10.5, it has been seen that a flow of 2 ACFM per man is proper to maintain carbon dioxide in the 0.005 ATA range. Figure 10.7 shows that ejector flow ratios from 20 to 25 may theoretically be obtained without requiring prohibitively large supply pressures. At 165 ft, 2 ACFM flow is 12 SCFM, and at a flow ratio of 20, a supply flow of 0.6 SCFM is required. Examination of figure 10.6 shows that 0.6 SCFM supply flow will keep the chamber oxygen level quite close to 20 percent. This is desirable, since effective recompression treatment by standard air tables is not possible if the breathed gas is markedly low in oxygen. Bends recurrence rate is already high using the air tables, and greatly lowering the oxygen level would tend to increase the recurrence rate.

An ejector was built and tested to be sure that the theoretical approach was valid. Results of flow tests may be seen in figure 10.8. Happily, the ejector performance was completely adequate and will be incorporated without change into the chamber prototype.

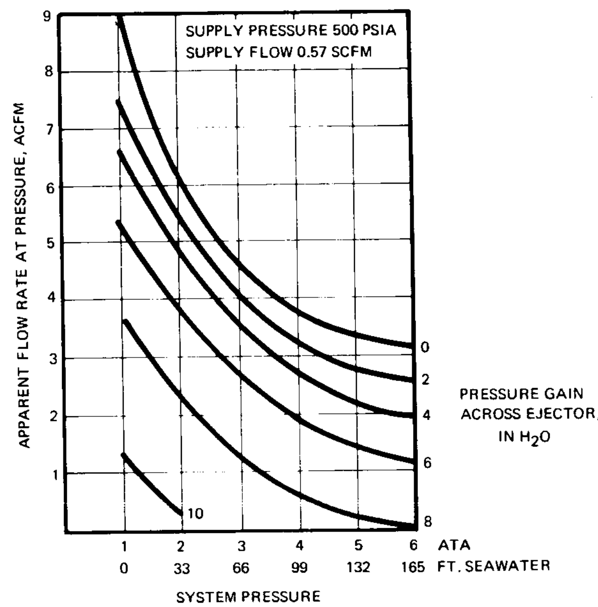

Figure 10.8 *Actual ejector performance.*

Actual System Flows

Because piping systems may not behave according to estimates of their characteristics, provision has been made for addition of a flow meter to the flow circuit. Without the meter orifice, it is estimated that system pressure drop will be in the 1 to 2 in. of water range, including canister losses at 6 ATA. Addition of the meter orifice will provide a pressure drop that will be used in conjunction with a differential pressure gage for flow measurement. An orifice of 0.45-in diam will theoretically produce about another 2 in. of water pressure drop at 2 ACFM and 6 ATA.

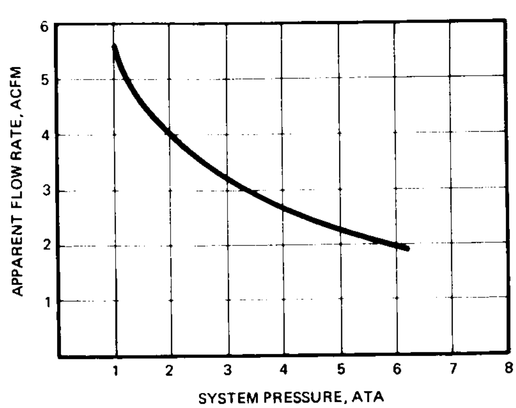

Figure 10.9 *Predicted system performance.*

When estimated system characteristics are correlated with the ejector characteristics shown in figure 10.8, the performance of the entire system can be estimated. It is shown in figure 10.9.

Supply and Exhaust Gas Flow Rates

Supply and exhaust gas flow during semiclosed-circuit operation has already been determined to be about 0.6 SCFM. For open-circuit operation, and for standard rates of ascent and descent, the flow rates may be calculated as follows.

Descent. At the standard descent rate of 25 ft/min, a chamber must gain pressure at the rate of 25/33 ATA/min; thus for an 18.3 cu ft chamber,

$$\text{Required supply flow} = \frac{25}{33} \times 18.3 = 14 \text{ SCFM during descent}$$

Normal Open-Circuit Ventilation. Normal open-circuit ventilation will be at least 2 ACFM as measured at the chamber depth and indicated by the built-in orifice meter. At 165 ft, or 6 ATA, this requires 12 SCFM.

Ascent. During ascent, the standard procedure is to ascend at the rate of 1 min per decompression stop. During each ascent, the chamber loses

$$\frac{18.3}{33} = 0.555 \ \frac{\text{ft}^3 \text{ gas}}{\text{ft of depth}}$$

Thus, for a 20-ft stop, flow = 20 × 0.555 = 11.1 SCFM; for a 15 ft-stop, flow = 15 × 0.555 = 8.3 SCFM; for a 10-ft stop, flow = 10 × 0.555 = 5.6 SCFM. The most severe flow requirement is from 10 feet to surface, since at this depth driving pressure across the exhaust valve is least. A 1/4-in. orifice will pass 16 SCFM to atmosphere with a 5 psi driving pressure, 12 SCFM with 3 psi, 7 SCFM with 1 psi. This flow capacity is adequate to provide for all treatment stages except for the 10-ft-to-surface stop. In that case, it will take 2 or 3 min to complete the ascent. However, this ascent is not made until treatment is complete, and the extra minutes are of little consequence. An exhaust valve having an equivalent orifice size of 1/4 in. was correspondingly employed.

Supply Piping and Valves. All supply piping is short, and deliberately kept larger than restricting valves to minimize pressure drop. Valves have been sized to be the smallest valves that can pass the required flow, as this generally gives fineness of control over the entire flow range.

CO_2 Absorption

It was originally planned that carbon dioxide absorption would be effected by use of a radial-flow canister containing concentric cylinders of lithium hydroxide (for carbon dioxide) and activated charcoal or alumina (for odor and dust removal). However, because of its general availability in Navy diving operations, granular baralyme has been selected as the system carbon dioxide absorbent. Its prime drawback is that it has low efficiency at low temperatures, requiring more frequent canister changes in cold conditions than would lithium hydroxide.

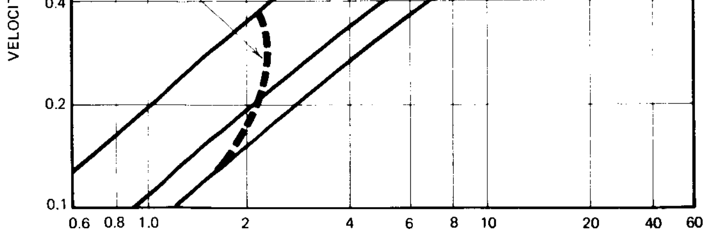

Figure 10.10 *Results of air flow tests conducted with granular baralyme.*

Present canister design is a cylinder 6-3/4-in. in diameter and 9-in. long. Flow is straight through vertically. Originally, the radial-flow approach was taken to minimize flow resistance, but flow tests showed such low resistance with straight-through flow that any reduction by design sophistication was unnecessary. Results of flow tests using baralyme in beds of different geometries are shown in figure 10.10.

Odors will be absorbed by a layer of activated charcoal located at one end of the baralyme bed. The carbon dioxide absorption capacity of the system is estimated to be at least 20 hr at 70° F and 10 hr at 32° F, the reduction occurring because of the reduced efficiency of baralyme at low temperatures. A transparent lid on the canister permits visual evaluation of the baralyme, which turns bluishwhite when exhausted. Results of canister performance tests are shown in figure 10.11.

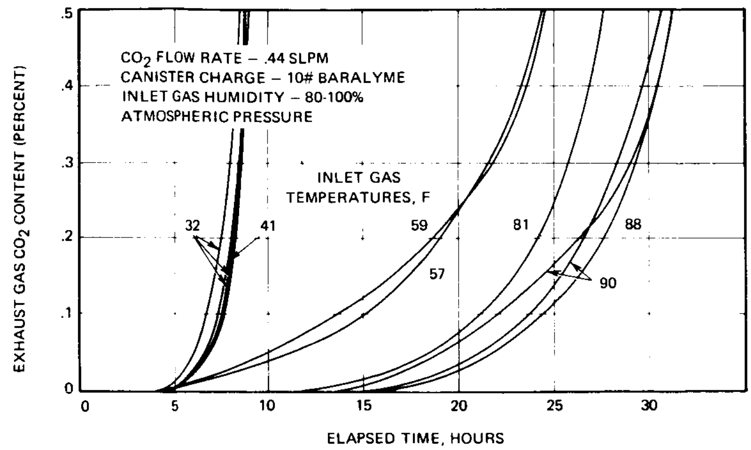

Figure 10.11 *Carbon dioxide scrubber test data.*

Humidity and Temperature

Because the human respiratory system effectively humidifies gas passed through it and because the chemical reaction in the canister produces moisture, after a time, the chamber will reach a high level of humidity; indeed it is probable that system humidity will be 90 to 100 percent. Some reduction of this will be caused by the addition of the ejector primary flow, but this flow is only 1/10 to 1/40 the total flow in the system. Therefore, the atmosphere will be very humid. This has been confirmed by experiments conducted using a similar chamber. Use of dessicants could reduce the humidity, but this could give the occupant an uncomfortably dry atmosphere to breathe, and would add somewhat to system complexity.

Temperature will be regulated by placing the chamber in a location where the surroundings are at a comfortable temperature, if possible. If not possible, the occupant must grit his teeth and be cheered by the thought that discomfort is preferable to decompression sickness. Experiments yet to be run will establish the true levels of temperature reached in the chamber. Present estimates indicate that interior temperatures will be 10° to 15° F higher than ambient, depending on chamber color, environment, and occupant dress.

Effect of Altitude on Operation

Because the chamber is controlled by ambient pressure-sensing regulators and pressure is read on an ambient-pressure-sensing gage, the chamber interior will drop in pressure during flight in an unpressurized aircraft. To keep ambient pressure change from affecting the chamber occupant, an instruction plate will be fixed to the control panel instructing the operator to add 1 ft of depth to the chamber for every 1000 ft of aircraft cabin altitude. This correction is valid to 15,000 ft altitude. Above that altitude, it is too cold to fly the chamber in ambient conditions.

APPLICATION OF THE SYSTEM

The recompression system discussed here may be used both to treat a diver for decompression sickness or to transport him to a larger chamber complex.

Stops		Bends–Pain only				Serious Symptoms	
Rate of descent–25 ft. per min. Rate of ascent–1 minute between stops		Pain relieved at depths less than 66 ft. Use table 1–A if O_2 is not available		Pain relieved at depths greater than 66 ft. Use table 2–A if O_2 is not available. If pain does not improve within 30 min. at 165 ft the case is probably not bends. Decompress on table 2 or 2–A.		Serious symptoms include any one of the following: 1. Unconsciousness. 2. Convulsions. 3. Weakness or inability to use arms or legs. 4. Air embolism. 5. Any visual disturbances. 6. Dizziness. 7. Loss of speech or hearing. 8. Severe shortness of breath or chokes. 9. Bends occurring while still under pressure.	
						Symptoms relieved within 30 minutes at 165 ft. Use table 3	Symptoms not relieved within 30 minutes at 165 ft. Use table 4
Pounds	Feet	Table 1	Table 1-A	Table 2	Table 2-A	Table 3	Table 4
73.4	165	....	....	30 (air)	30 (air)	30 (air)	30 to 120 (air)
62.3	140	....	....	12 (air)	12 (air)	12 (air)	30 (air)
53.4	120	....	....	12 (air)	12 (air)	12 (air)	30 (air)
44.5	100	30 (air)	30 (air)	12 (air)	12 (air)	12 (air)	30 (air)
35.6	80	12 (air)	12 (air)	12 (air)	12 (air)	12 (air)	30 (air)
26.7	60	30 (O_2)	30 (air)	30 (O_2)	30 (air)	30 (O_2) or (air)	6 hrs. (air)
22.3	50	30 (O_2)	30 (air)	30 (O_2)	30 (air)	30 (O_2) or (air)	6 hrs. (air)
17.8	40	30 (O_2)	30 (air)	30 (O_2)	30 (air)	30 (O_2) or (air)	6 hrs. (air)
13.4	30	↓	60 (air)	60 (O_2)	2 hrs. (air)	12 hrs. (air)	First 11 hrs. (air) Then 1 hr. (O_2) or (air)
8.9	20	5 (O_2)	60 (air)	↓	2 hrs. (air)	2 hrs. (air)	First 1 hr. (air) Then 1 hr. (O_2) or (air)
4.5	10	↓	2 hrs. (air)	5 (O_2)	4 hrs. (air)	2 hrs. (air)	First 1 hr. (air) Then 1 hr. (O_2) or (air)
Surface		↓	1 min. (air)	↓	1 min. (air)	1 min. (air)	1 min. (O_2)

Time at all stops in minutes unless otherwise indicated.

Figure 10.12 *Air treatment tables from U.S. Navy diving manual.*

If the chamber is used for treatment of the diver, pressurization and depressurization will follow the schedule prescribed in the U.S. Navy diving manual (fig. 10.12). Oxygen content of the chamber and gas usage will vary as shown in figure 10.13, a printout of a computer program that combines equation (3) with the diving manual's decompression schedules. The diving manual's table 4 is illustrated in figure 10.13 because it requires the longest treatment time—the other three tables effect similar results.

Of particular interest in figure 10.13 is the far right-hand column. Once the chamber has been pressurized to 165 ft, it may operate for 4 hr on 136 cu ft of gas, which can be supplied by a single pair of standard Navy 90 cu ft scuba bottles. Put in another way, the chamber can be pressurized and go on to operate for 3 hr using only a single 240 cu ft air flask. If open-circuit operation were used, the same air flask would last only 12 min. A clear improvement in gas economy is evident.

If the chamber is used only as a transportation capsule, the occupant will be pressurized until relief is reached. The chamber will be maintained at that pressure until the chamber can be mated to a larger treatment chamber and the patient removed. Figure 10.14 shows the variation in oxygen content in systems pressurized to different initial pressures and held at those pressures while circulation is maintained by the ejector air flow.

A variation of the same program is shown in figure 10.15, which illustrates the enormous oxygen capacity of the system. If the system is pressurized to 40 ft or more, operation can safely be maintained for more than 8 hr with the addition of no gas at all, providing circulation is maintained, say by a check-valved oral-nasal mask connected to the circulation piping. However, use of this mode of operation will result in depressed oxygen partial pressures, making the air tables unusable for this system.

FUTURE WORK

The chamber design is, at the time of this writing (May, 1971), being reviewed by the Certification Board, under the authority of the U.S. Navy Experimental Diving Unit. Upon approval of the design, construction will begin. We hope to have an operable chamber built by August 1971, and to begin fullscale experimental evaluation of it at that time.

Ejector air flow = 16.1 SLM = 0.57 SCFM
Weight of chamber occupant = 165 lb
Oxygen consumed by occupant = 0.25 SLM
Chamber volume = 18.3 ft^3

Depth, ft	*Time, hr*	*pO_2 ATA*	*Percent oxygen*	*Gas used cu/ft*
165	0	1.26	21.	78.2788
165	2	1.22179	20.3632	146.547
140	2	1.06753	20.3632	146.547
140	2.5	1.06161	20.2504	163.615
120	2.5	.938883	20.2504	163.615
120	3	.934127	20.1478	180.682
100	3	.812019	20.1478	180.682
100	3.5	.808307	20.0557	197.749
80	3.5	.686757	20.0557	197.749
80	4	.683977	19.9745	214.816
60	4	.562919	19.9745	214.816
60	10	.556766	19.7562	419.622
50	10	.496899	19.7562	419.622
50	16	.496842	19.754	624.427
40	16	.436981	19.754	624.427
40	22	.436981	19.7539	829.233
30	22	.377121	19.7539	829.233
30	34	.377121	19.7539	1238.84
20	34	.31726	19.7539	1238.84
20	36	.31726	19.7539	1307.11
10	36	.2574	19.7539	1307.11
10	38	.2574	19.7539	1375.38
0	38	.197539	19.7539	1375.38
0	38.0167	.197539	19.7539	1375.95

Figure 10.13 *Gas flows and usage for air decompression by Table 4.*

Weight of chamber occupant = 165 lb
Oxygen consumed by occupant = 0.25 SLM
Chamber volume = 18.3 ft^3

	Oxygen percentages at depths of			
Time, hr	*165 ft*	*100 ft*	*40 ft*	*0 ft*
0	21.	21.	21.	21.
.5	20.7959	20.7087	20.521	20.18
1	20.6253	20.4855	20.2262	19.8996
1.5	20.4825	20.3145	20.0446	19.8037
2	20.3632	20.1834	19.9329	19.771
2.5	20.2634	20.083	19.8641	19.7598
3	20.18	20.0061	19.8218	19.7559
3.5	20.1102	19.9471	19.7957	19.7546
4	20.0518	19.902	19.7796	19.7542
4.5	20.0031	19.8674	19.7698	19.754
5	19.9623	19.8409	19.7637	19.754
5.5	19.9281	19.8205	19.7599	19.754
6	19.8996	19.805	19.7576	19.7539
6.5	19.8757	19.793	19.7562	19.7539
7	19.8558	19.7839	19.7553	19.7539
7.5	19.8391	19.7769	19.7548	19.7539
8	19.8252	19.7715	19.7545	19.7539
8.5	19.8135	19.7674	19.7543	19.7539
9	19.8037	19.7643	19.7541	19.7539
9.5	19.7956	19.7619	19.7541	19.7539
10	19.7888	19.76	19.754	19.7539
10.5	19.7831	19.7586	19.754	19.7539
11	19.7783	19.7575	19.754	19.7539
11.5	19.7743	19.7567	19.754	19.7539
12	19.771	19.756	19.754	19.7539
12.5	19.7682	19.7555	19.754	19.7539
13	19.7659	19.7552	19.7539	19.7539
13.5	19.7639	19.7549	19.7539	19.7539
14	19.7623	19.7547	19.7539	19.7539
14.5	19.7609	19.7545	19.7539	19.7539
15	19.7598	19.7544	19.7539	19.7539
15.5	19.7588	19.7543	19.7539	19.7539
16	19.758	19.7542	19.7539	19.7539

Supply air flow = 0.57 SCFM

Figure 10.14 *Variation of percent O_2 with time in a recompression chamber at various depths.*

Weight of chamber occupant = 165 lb
Oxygen consumed by occupant = 0.24 SLM
Chamber volume = 18.3 ft^3

	Oxygen percentages at depths of			
Time, hr	*165 ft*	*100 ft*	*40 ft*	*0 ft*
0	21.	21.	21.	21.
.5	20.7857	20.6808	20.4175	19.7057
1	20.5709	20.3603	19.8307	18.3902
1.5	20.3555	20.0386	19.2396	17.0532
2	20.1395	19.7155	18.6442	15.6942
2.5	19.9229	19.3911	18.0443	14.313
3	19.7057	19.0655	17.44	12.9091
3.5	19.4879	18.7385	16.8313	11.4823
4	19.2696	18.4102	16.2181	10.0321
4.5	19.0506	18.0805	15.6003	8.55808
5	18.8311	17.7495	14.978	7.05995
5.5	18.6109	17.4172	14.3511	5.53727
6	18.3902	17.0836	13.7196	3.98964
6.5	18.1689	16.7486	13.0835	2.41666
7	17.9469	16.4122	12.4426	.817918
7.5	17.7244	16.0745	11.797	
8	17.5013	15.7354	11.1467	
8.5	17.2775	15.3949	10.4915	
9	17.0532	15.0531	9.83156	
9.5	16.8282	14.7099	9.16673	
10	16.6026	14.3653	8.49699	
10.5	16.3764	14.0193	7.82232	
11	16.1496	13.6719	7.14267	
11.5	15.9222	13.3232	6.45801	
12	15.6942	12.973	5.7683	
12.5	15.4656	12.6214	5.07351	
13	15.2363	12.2683	4.37359	
13.5	15.0064	11.9139	3.66851	
14	14.7759	11.558	2.95824	
14.5	14.5448	11.2006	2.24272	
15	14.313	10.8419	1.52193	
15.5	14.0806	10.4816	.795831	
16	13.8476	10.12		

Supply air flow = 0

Figure 10.15 *Variation of percent O_2 with time in a recompression chamber at various depths.*

BIBLIOGRAPHY

1. Anon: U.S. Navy Diving Manual. NAVSHIPS 0994-001-9010, March, 1970.
2. Anon: Compressed Air Data. Compressed Air Magazine, New York, 1960.
3. Anon: Flow of Fluids Through Valves, Fittings, and Pipe. Technical Paper 910, The Crane Co., Chicago, Illinois.
4. Comroe, J. H.; Forster, R. E.; Dubois, A. B.; Briscoe, W. A.; and Carlsen, E.: The Lung. Year Book Medical Publishers Inc., Chicago, 1962.
5. Riegel, P. S.: Liter Flow and Mix Selection in Semiclosed-Circuit Scuba. Marine Tech. Soc. J., March/April, 1970.
6. Caudy, D. W.; and Glasgow, J. S.: Final Report on Portable Recompression Chamber Environmental Control System Study to Supervisor of Diving, United States Navy, Battelle Memorial Institute, July 31, 1970.
7. Caudy, D. W.: Design Review Report for Portable Recompression System to U.S. Navy, Supervisor of Diving, Battelle Memorial Institute, April, 1971.
8. Alexander, J. M., assistant submarine medical officer: personal comm.
9. Milwee, W. I., supervisor of diving: personal comm.
10. Lower, B. R.: Removal of CO_2 from Closed-Circuit Breathing Apparatus, Equipment for the Working Diver. Symposium, Battelle Columbus Laboratories, Columbus, Ohio, 1970.
11. Keenan, J. H.; and Neumann, E. P.: A Simple Air Ejector. J. Appl. Mech., June, 1942.