N72-27108

2

DESIGN CONSIDERATIONS FOR DIVERS' BREATHING GAS SYSTEMS

O. R. Hansen
Office of the U.S. Navy Supervisor of Diving
Naval Ships Systems Command

INTRODUCTION

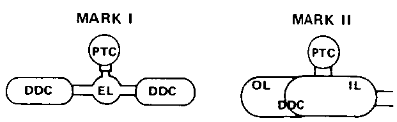
The advent of deep dive systems and saturation diving has necessitated the careful planning and design of breathing gas systems. For saturation diving, the divers' enclosures must be pressurized to, and sustained at, a pressure equivalent to the depth at which the mission operations are to be performed. Thus, the flow rate itself is not a significant design parameter. The initial pressurization is normally conducted at a relatively low rate, and the mission duration can be up to 10 days.

Breathing gas, normally a helium-oxygen mixture, must be available to effect the required pressurization. There also must be sufficient gas to supply the breathing apparatus used by the deployed divers, as well as a reserve supply for treating decompression sickness.

This paper discusses some of the design methods used to establish the gas storage, mixing, and transfer requirements for existing deep dive systems.

DEEP DIVE SYSTEMS

Table 2.1 *Design parameters for gas requirements in Mark I and II deep dive systems.*



ENCLOSURE	VOLUME – FT^3	VOLUME – FT^3
Deck Decompression Chamber (DDC)	321.0 (1 chbr)	765.0
Personnel Transfer Capsule (PTC)	144.0	227.0
Entrance Lock (EL)	103.79	235.0
Supply Lock (SL)	1.61	3.0
MARK I		
EL to DDC Trunk	3.00	—
EL to PTC Trunk	9.28	—
PTC Trunk	8.15	—
MARK II		
DDC Transfer Trunk		16.0
PTC Transfer Trunk		13.0
PTC FLASKS		
Helium	20.0	30.0
Oxygen	6.0	6.0
Mixed Gas	10.0	24.0
Scrubber – DDC	2.90	3.00

OTHER PARAMETERS	MARK I	MARK II
Design Depth of Diving Mission	850 feet	1000 feet
Diving Man-Hours	4*	8**

*The Mark I PTC is normally used with a three-man crew: a capsule operator (tender), a diver and a standby diver. One descent of PTC for a diving mission normally includes 4 hours of bottom time, 4 hours handling time and 2 hours for recharging PTC flasks. Two alternating crews are employed on a saturation mission with one crew being maintained at pressure in the DDC.

**The Mark II PTC can accommodate a four-man crew: a capsule operator (tender), a standby diver and 2 working divers. The 2 working divers provide an eight man-hour diving capability for one deployment of the PTC.

The U.S. Navy has two major deep dive systems (DDS), the Mark I and Mark II. These systems differ in the number of divers they will support, in enclosure volume, and in system arrangement. These differences reflect intended system application and installation: The Mark I was designed primarily to support the large object salvage system (LOSS), and the Mark II was designed to support submarine rescue operations. Table 2.1 provides the design parameters for establishing the gas requirements of these two systems.

The gas required to support missions of maximum duration must be stored aboard the diving platform or mother ship and must be available in a readily transferable state to permit performance of any mission within the design capability of the system.

The usual gas supply is a mixture of helium and oxygen, with a small quantity of nitrogen present in the system atmosphere prior to pressurization. The enclosure environment is maintained at ∿0.3 atm oxygen partial pressure throughout the mission, and the oxygen required to replace that consumed by the divers in the enclosures is only about 1 SCF[1] hr. Thus, analysis of helium requirements receives the most attention.

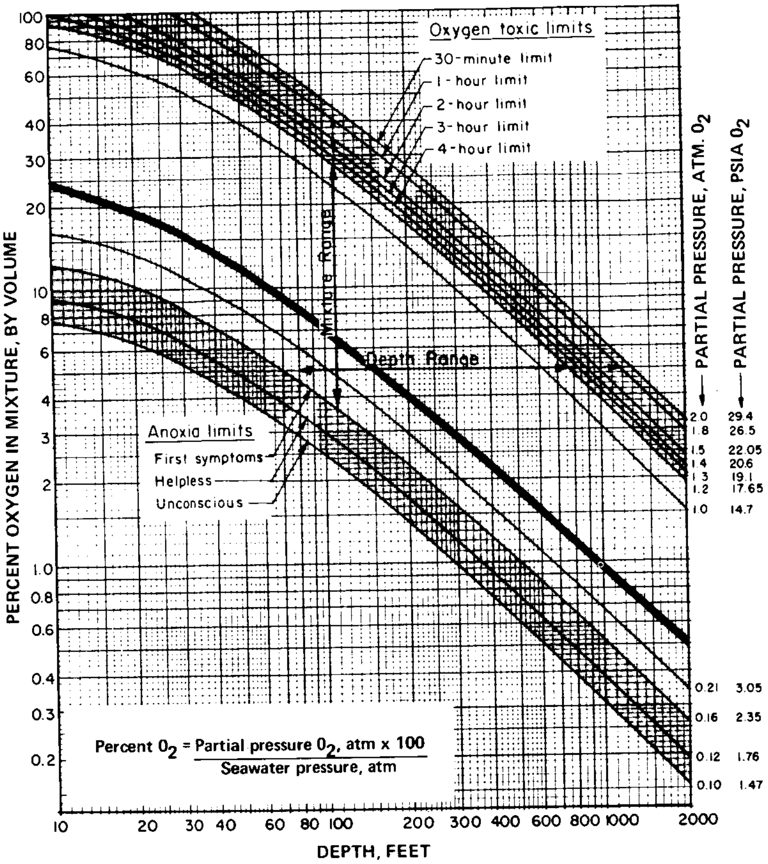


Figure 2.1 *Percentage of O_2 in breathing mixture as a function of depth and O_2 partial pressure.*

Systems that use a semiclosed diver breathing apparatus are an exception, however, and demand a more extensive analysis of oxygen requirements. Figure 2.1 relates the percentage of oxygen in the breathing mixture to depth, and to oxygen partial pressure in both psia and atm. The curves show a large area within which mixtures are physiologically acceptable. The oxygen concentration must be maintained within the concentration range shown in this figure. In the semiclosed apparatus, mixtures must provide an adequate liter flow through the system to supply metabolic oxygen for the diver as well as maintain an oxygen concentration within tolerable limits. This system was adequately described in the initial life support systems conference but the definition of gas mixture oxygen concentration and liter flow (fig. 2.2) was developed later. It is again evident, however, that for deep diving, the availability of helium is of paramount importance. To avoid toxicity, the oxygen percentage must decrease as depth increases so that the quantity of helium supplied with the oxygen will increase with depth.

The Mark 10 closed-circuit breathing apparatus (see paper 8), appears to be an optimum system in which essentially only the oxygen to support the diver's metabolic requirements must be provided. This will simplify the establishment of gas storage system requirements.

GAS STORAGE SYSTEMS

High Pressure Storage Systems

Utilizing design principals applied in nuclear submarines, the original diving gas storage systems were designed as high pressure stored gas systems. Recognizing that the submarine environment is at one atmosphere and that the diving system is at the diving depth pressure the significance of storage pressure and volume are not readily apparent. Pressure and volume effects both space and weight of the system and a method to relate these parameters is presented in this section.

[1]SCF = standard cubic ft; helium at 70° F and 14.7 psia.

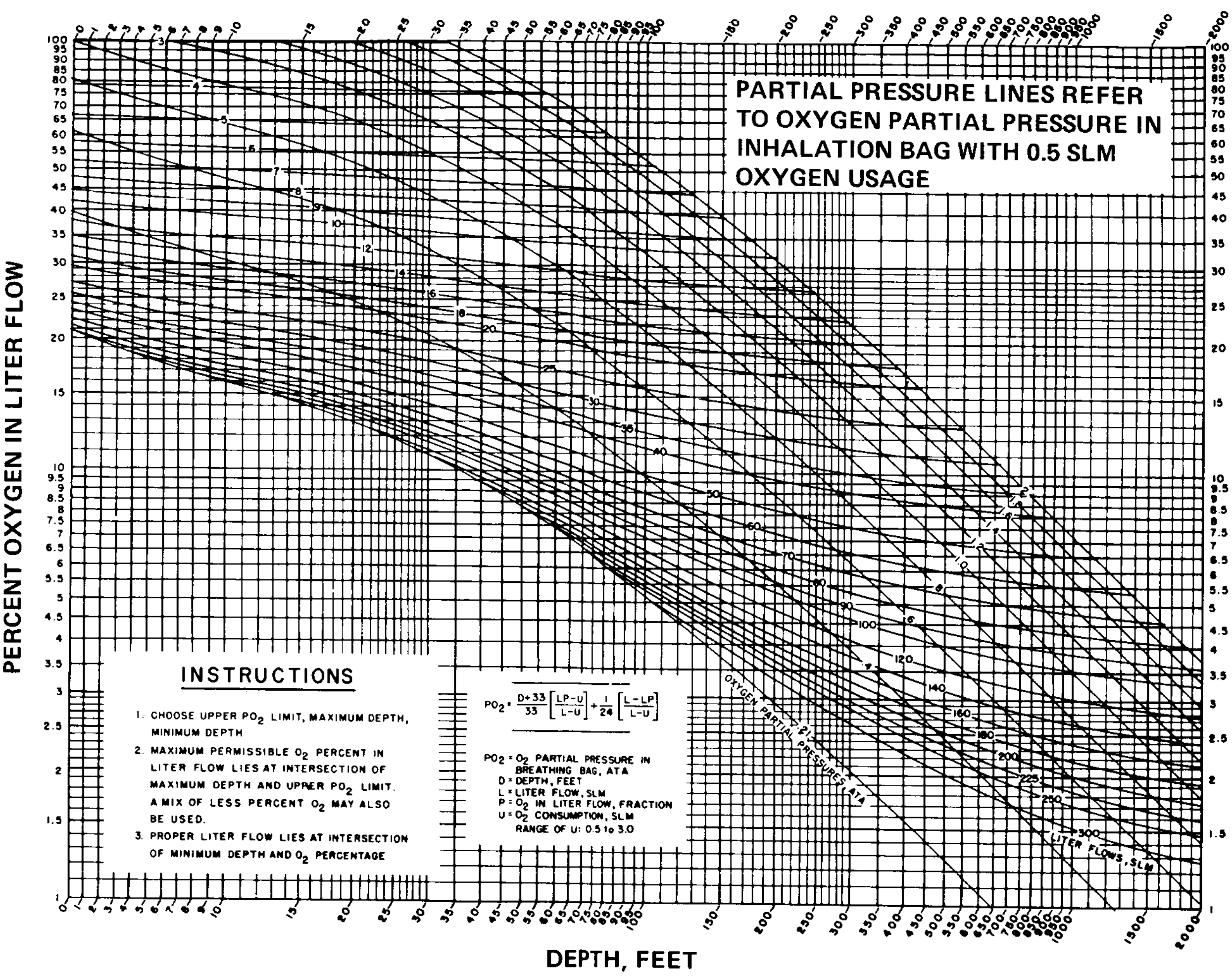


Figure 2.2 *Liter flow and* O_2 *percentage for semiclosed circuit breathing apparatus.*

An adequate supply of gas must provide for the maximum mission as well as gas reserves needed in emergency. Unless provision is made for gas transfer, the storage volume will contain gas at equilibrium pressure with the depth of the diving mission. A second consideration is that helium, oxygen, and mixtures thereof deviate significantly from ideal gas, thus precluding application of simple gas laws. Figure 2.3 indicates that less than 90 percent of the helium predicted by ideal gas laws will be stored in a 3000 psi volume where real gas properties exist. This deviation has prompted the application of various techniques to account for real gas characteristics in the design of gas storage systems.

The importance of this deviation in maintaining the permissible mixtures was the subject of considerable study leading to the publication of a U.S. Navy Diving-Gas Manual (ref. 1), which has been invaluable in the design of breathing gas systems.

The use of a single virial coefficient (ref. 2) for determining helium storage requirements has been expedient in developing computer analyses of the many systems being designed. The helium properties established by means of this coefficient, have been compared to those in the manual, which were obtained with the use of additional virial coefficients. Properties obtained with the

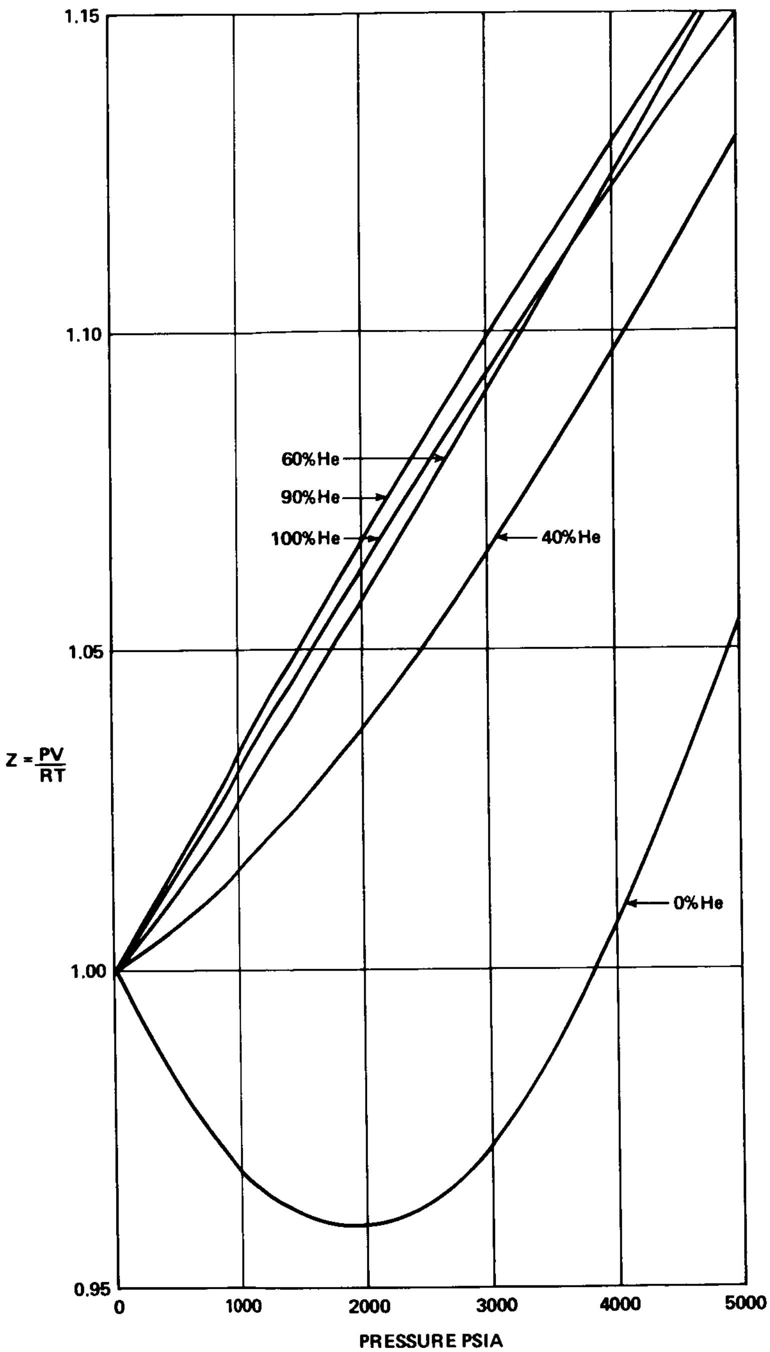


Figure 2.3 *Deviation of* HeO_2 *mixtures from ideal gas laws.*

single coefficient show a maximum variation of 0.12 percent from those in the manual. The computer program used for this analysis and the resulting output data are given in appendix A.

The application of this single coefficient established the compressibility factor that can be introduced into the ideal gas equation

$$PV = WRT$$

The compressibility factor is related to the pressure times B for any isotherm as follows. The real gas compressibility factor is

$$Z = \frac{PV}{RT}$$

where

$$Z = (1 + BP)$$

and

$$B = \textit{virial coefficient}$$

The density is then

$$\lambda = \frac{P}{(1 + BP)RT}$$

and the pressure will be

$$P = \frac{\lambda TR}{1 - B\lambda RT}$$

which, applied in analyses, provides helium properties approaching real properties.

Once the gas property data have been determined for various state points existing within the diving system, effort can be directed toward establishing the system requirements.

Mark II DDS specifications dictate that 306,000 SCF of helium be available from the storage system at pressures above 200 psig. This gas supply is intended to support the two systems installed in the submarine rescue ships, ASR 21 and ASR 22. These are catamaran type ships, and half of the gas would be available to support a 10-day saturation mission in a single Mark II DDS installed in one hull.

Numerous studies were conducted to find the best method of storing this gas. Desired storage pressure, individual flask capacity, and storage bank arrangements were analyzed to arrive at the storage system as currently defined. In general, stored gas is contained in seamless steel pressure vessels designed according to Department of Transportation regulations.

The criteria for flasks used by the U.S. Navy are contained in a military specification (ref. 3); the pressure vessels are restricted to 3000 and 5000 psi working pressures and geometry defined by type. Investigation indicated alternative configurations and rated pressures could be obtained, and a limited optimization was performed within the capability.

To optimize the design of the cylinders it is necessary to define the stresses due to internal pressure in closed cylinders. Thus, an analysis for this study to obtain the stress in the cylinder wall was based on the fact that for a cylinder with other than very thin walls under internal pressure, the stress varies from a maximum at the inner surface to a minimum at the outer surface. The analysis also took into account the axial deformations, which affect the load capability of the material.

The following equations, known as Clavarino's equations, will provide the wall thickness to attain 67 percent of the material's ultimate strength at a test pressure equal to 5/3 the design pressure. The design pressure is equal to the pressure of the gas stored in the flask at standard conditions.

$$S_t' = (1 - 2m)\,a + \frac{(1 + m)\,b}{r^2}$$

$$S_r' = (1 - 2m)\,a - \frac{(1 + m)b}{r^2}$$

where

s_t' tangential stress, psi
s_r' radial stress, psi
m Poisson's ratio of lateral contraction
r radius at any point in the wall, in.
a,b constraints for any given values of pressures and diameters such that

$$a = \frac{P_i d_i^2 - P_o d_o^2}{d_o^2 - d_i^2}$$

$$b = \frac{d_i^2 d_o^2}{4} \left(\frac{P_i - P_o}{d_o^2 - d_i^2} \right)$$

where

d_i inside diam, in.
d_o outside diam, in.
P_i internal pressure, psi
P_o external pressure, psi

When a and b are evaluated, and when $d_i/2$ is substituted for r the equation of the thickness is

$$t = \frac{d_i}{2}\left[\sqrt{\frac{s_t' + (1 - 2m)\ P_i}{s_t' - (1 + \ m)\ P_i}} - 1\right]$$

where

s_t' = permissible working (tangential) stress in tension, psi

If, the end closure is assumed equivalent in thickness to the cylindrical walls and the normal corrosion allowance of 0.065 in. is added to wall thickness, the weight can be determined from the external volume less the internal volume times the density of the material used in fabrication. In the analyses, the outer diameter was maintained constant at 18, 20, 22, and 24 in. The cylinder configuration is shown in figure 2.4.

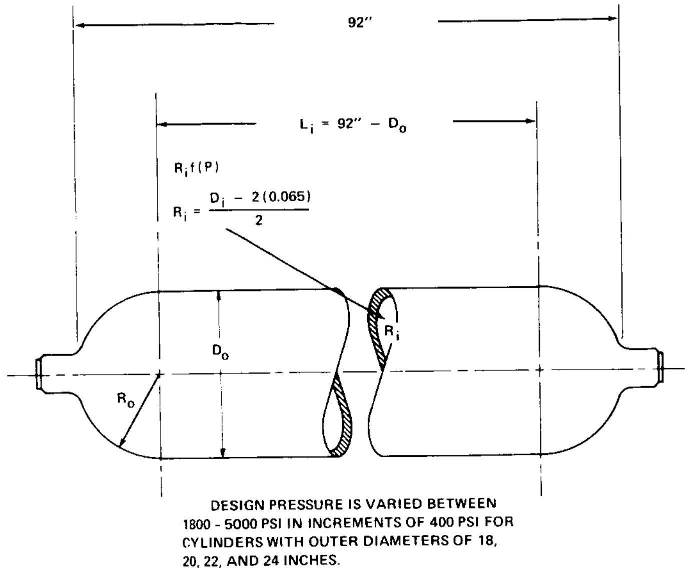


Figure 2.4 *Gas storage flask configuration used for* He *capacity and weight.*

The results of the analyses provide the wall thickness, internal volume, and weight for cylinders for each of the four diameters and the various design pressures.

These results are incorporated in the computer program for determining the total gas available above an equilibrium pressure equivalent to a given operating depth, established as 1000 ft. A ratio of available helium (in SCF) to each pound of metal in the storage system was obtained, which relates the gas storage pressure, diameter of the storage vessel, and gas contained at equilibrium pressure for each of the four outer diameters.

From the real gas properties for helium, one normally would expect less helium per pound of metal to be stored at higher pressures because of the increasing compressibility factor. This is correct, but the influence of reduced flask volume and diameter relative to the residual gas quantity is not immediately evident, although it becomes more apparent when the ratio is plotted versus storage pressure. The results are shown in figure 2.5, and the analytical data are given in appendix B.

The results indicate that the 24-in. diameter flask, with a design pressure ranging from 3400 to 3800 psi, is of optimum weight for helium storage in the system.

In general, this technique was applied in the selection of the gas flasks for the Mark II deep dive system aboard the ASR 21/22. Other factors in gas flask selection were the maximum available tooling capacity at the steel mill, which limited the outside diameter to 24 in. and the design pressure to 3800 psi, and the deck height, which restricted flask length to 8 ft (table 2.2).

Oxygen flasks were restricted to 3000 psi design pressures; the helium flasks had design pressures of 3800 psi. The helium available if filled to an equilibrium temperature of 100° F is 164,150 SCF; the quantity available above the minimum specified pressure is 153,860 SCF.

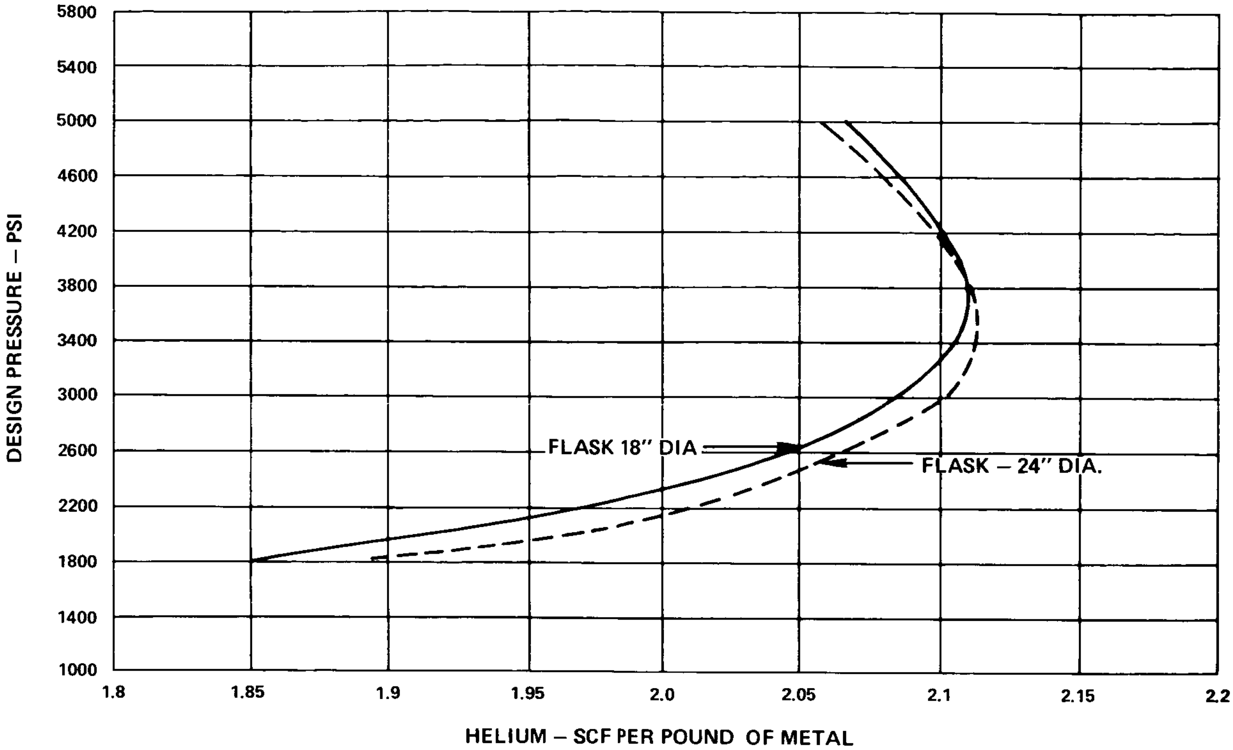


Figure 2.5 *Available He/lb of metal versus design pressure for flasks of 18- and 24-in. outer diam.*

Table 2.2 *System data for Mark II deep dive system aboard ASR 21/22.*

COMPRESSORS

USE	CAPACITY	QUANTITY	DISCH. PRESSURE	TYPE
Helium	0.45 CFM	2 per ship - 1 per hull	3800 PSIG max.	Diaphragm
Oxygen	Min. Displacement	2 per ship - 1 per hull	3800 PSIG max.	Booster

FLASKS

USE	VOLUME	QUANTITY	SIZE
Helium	16.88 cu. ft.	84 per ship - 42 per hull	8'0" Lg. x 24" O. D.
Oxygen	16.81 cu. ft.	24 per ship - 12 per hull	7'0" Lg. x 24" O. D.
Mixed Gases	16.88 cu. ft.	12 per ship - 6 per hull	8'0" Lg. x 24" O. D.
High Pressure Air	10.0 cu. ft.	20 per ship - 10 per hull	7'10" Lg. x 18" O. D.

Figure 2.6 illustrates the use of helium over a 10-day period in a saturation diving mission, relating the gas available for required events to that stored in the system. The analytical data resulting from these analyses are presented in appendix C. The results indicate that the helium stored is not quite sufficient to maintain the required reserve, and that flask filling and topping must be accomplished during replenishment.

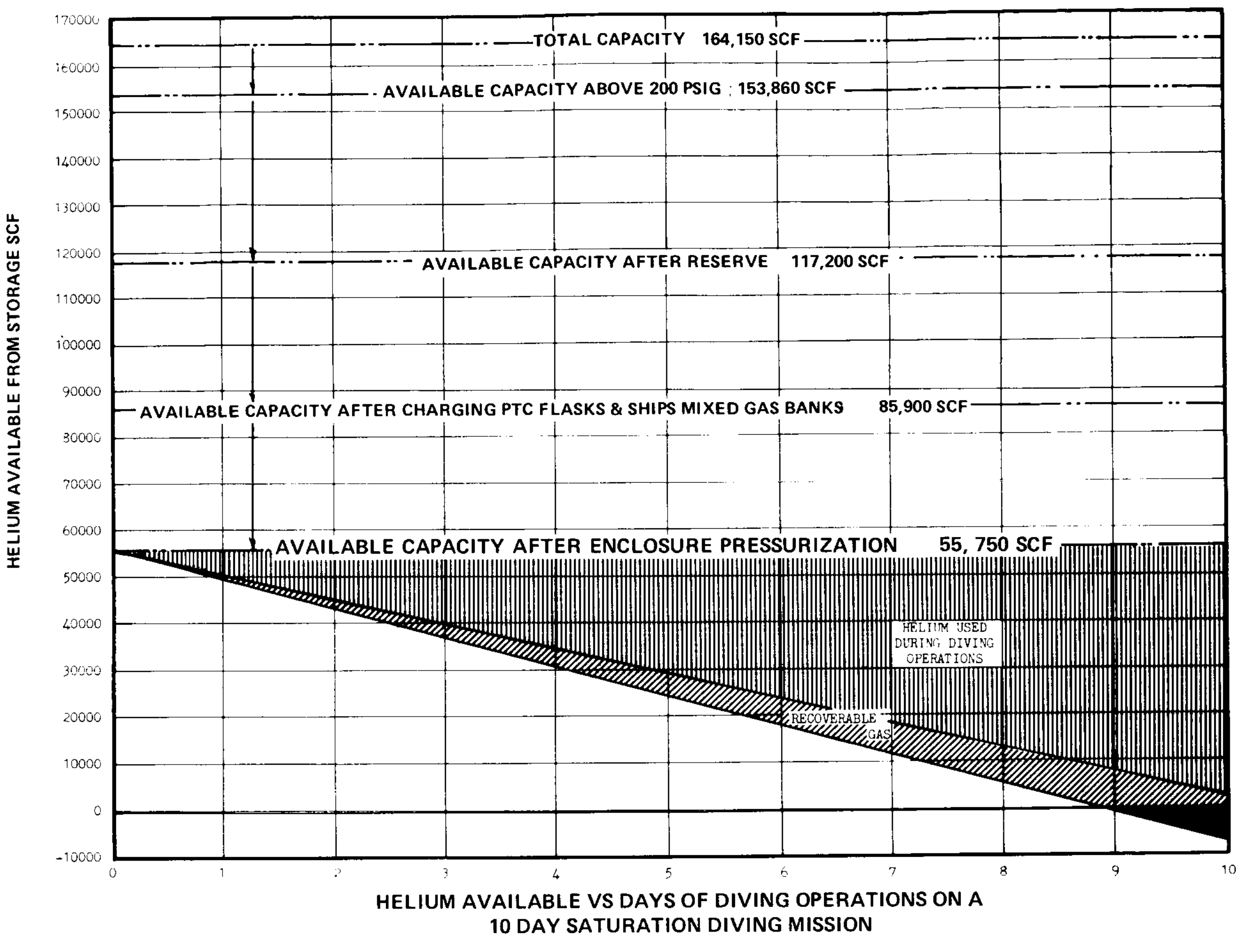


Figure 2.6 *Helium available versus days of diving operation on a 10-day saturation diving mission.*

Figure 2.7 shows the general arrangement of the Mark II system aboard an ASR 21/22 type platform.

Supercritical Storage Systems

One means of reducing gas storage system weight and volume is to convert the gas to liquid by cryogenic processes. It has been found that the low latent heat of vaporization and the high ΔT between the operational environment and liquid helium ($\sim\Delta T = 532° R$) preclude the long term storage of supercritical helium; however, its properties are such that lighter weight and lesser volume transport systems can be designed, particularly since the development of super insulations.

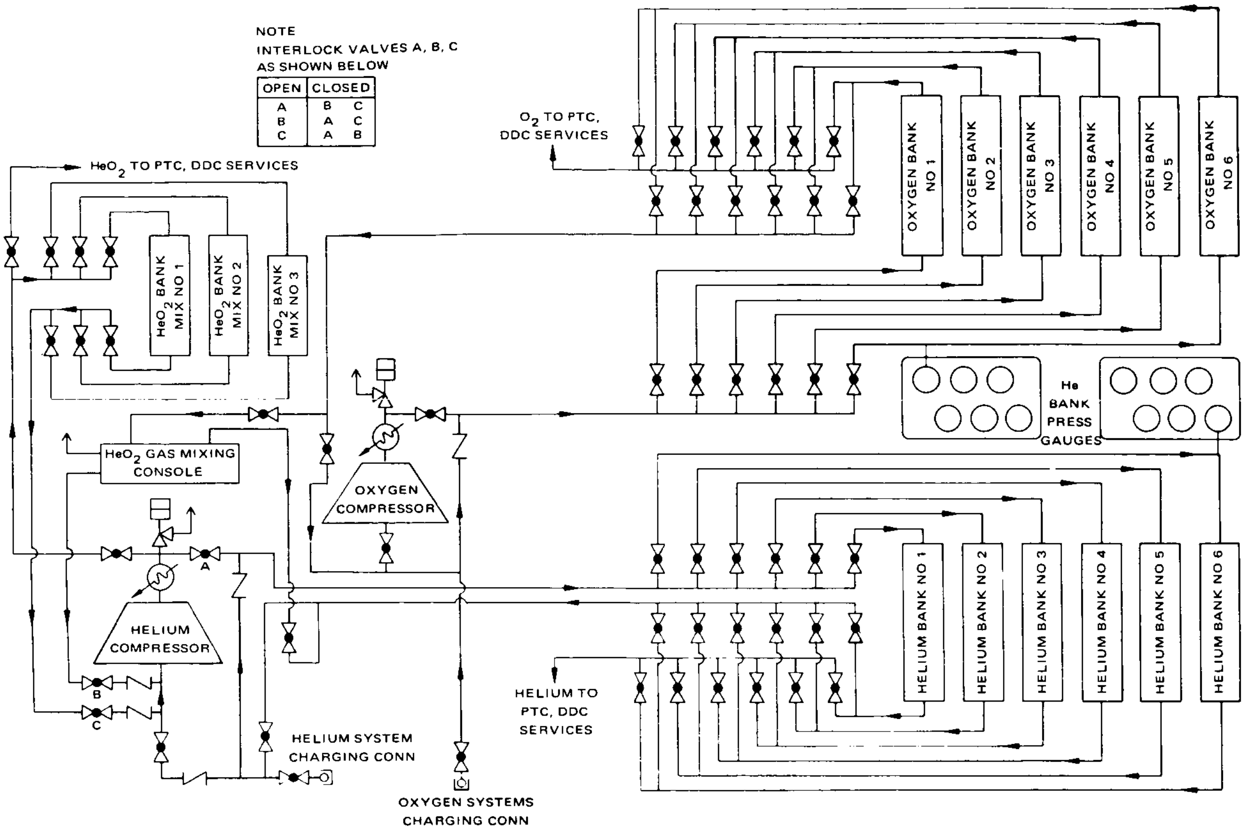


Figure 2.7 *Mark II deep dive system aboard ASR 21/22.*

The system concept is that a pressure vessel (fig. 2.8) is thermally insulated and filled with liquid helium at atmospheric pressure. The liquid inlet and gaseous vent are closed upon reaching the design capacity (in pounds of liquid); pressure then increases within the constant volume of the system in response to "heat leak" through the thermal insulation.

Then the pressure increase can be related as follows. From the first law of thermodynamics,

$$\Delta U = Q - W_k$$

and the definition of enthalpy

$$H = U + pv$$

where

Q heat added to the system
U internal energy function
W_k work done, by the system
P pressure
v specific volume = $\dfrac{\text{container volume}}{\text{total mass of liquid and vapor}}$

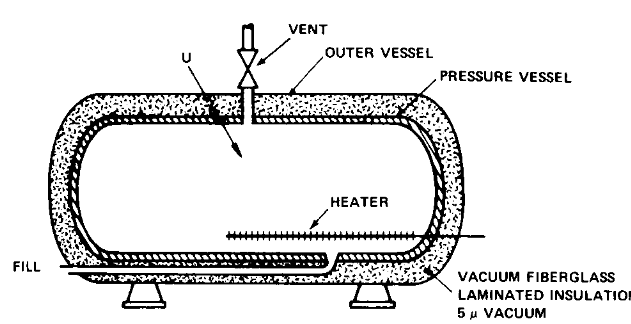


Figure 2.8 *Supercritical Dewar.*

Since the process is one of constant volume

$$W_k = 0$$

$$\Delta U = Q$$

or

$$Q = \Delta U = \Delta H + v\Delta p$$

Then the pressure rise is the result of the heat leak into the system, and the time for the system to reach the permissible working pressure is related to the thermal conductivity of the insulation. These principles were applied to a recently developed flyaway system to support the diving systems (fig. 2.9).

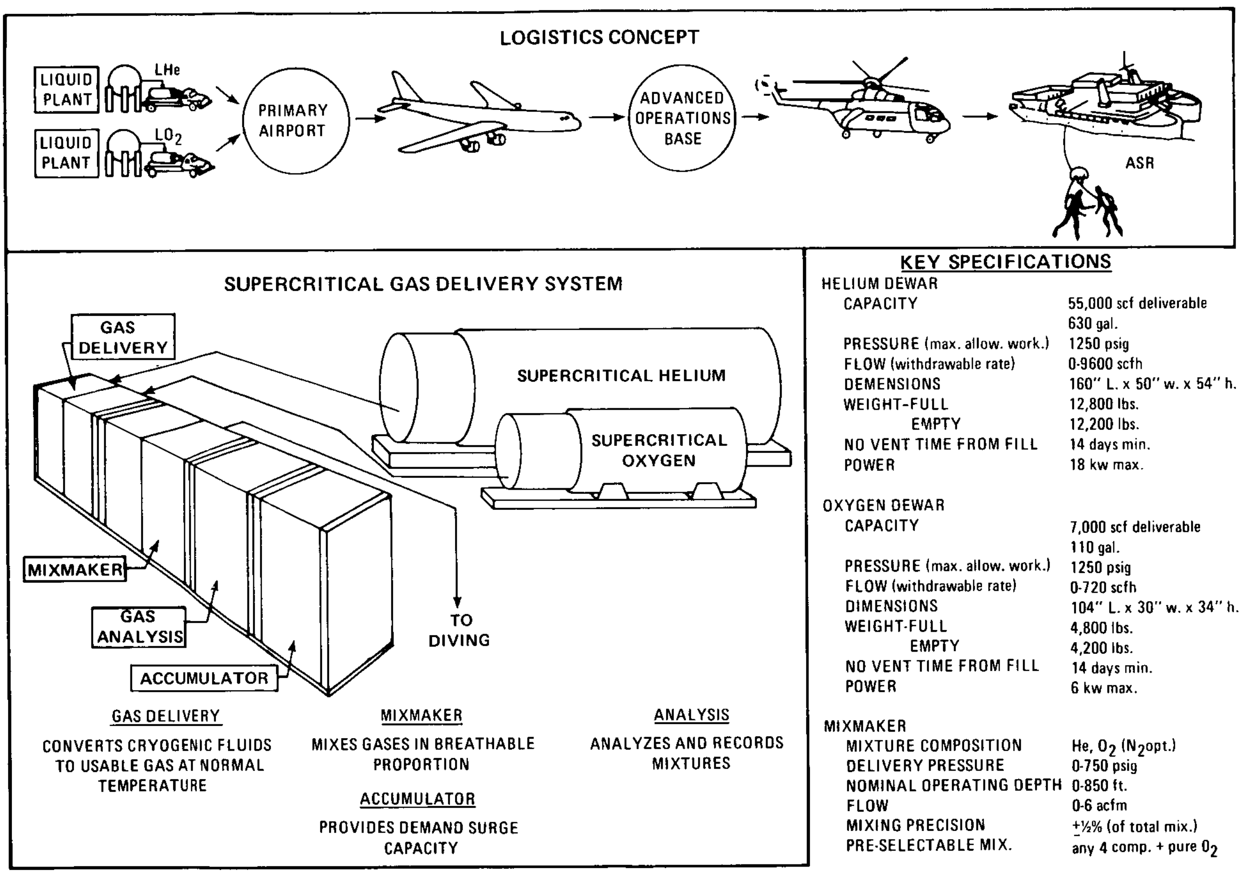


Figure 2.9 *Supercritical gas system for diving.*

Performance curves relating days to pressure increase are shown in figure 2.10.

When the previously stated relationship and helium property data from ref. 5 are applied, the helium temperature when the Dewar is at 1250 psi will be ~44° R. (Relationships of temperature and internal energy to pressure in a closed Dewar are shown in figure 2.11.) Therefore, any helium to be used in the diving system must be heated to a usable temperature. This is done in the gas delivery console. System weight is then full Dewar weight plus the delivery console or ~(12800 + 1300) = 14,100 and, based on their delivery criteria, there are ~4 SCF helium available per lb of metal in the system.

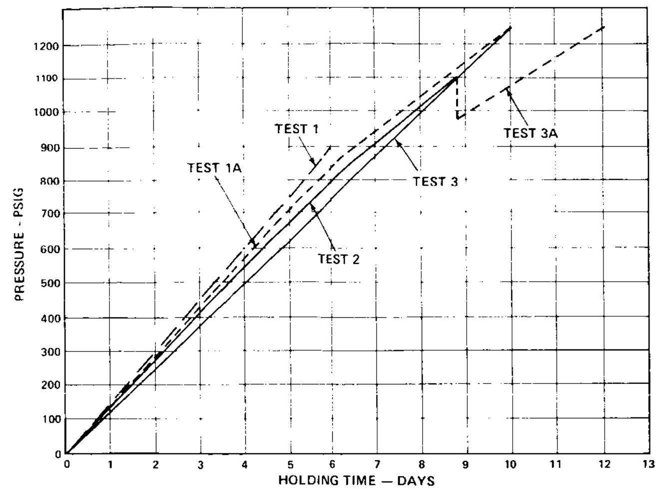


Figure 2.10 *Test results of pressure buildup versus time in one supercritical* He *Dewar.*

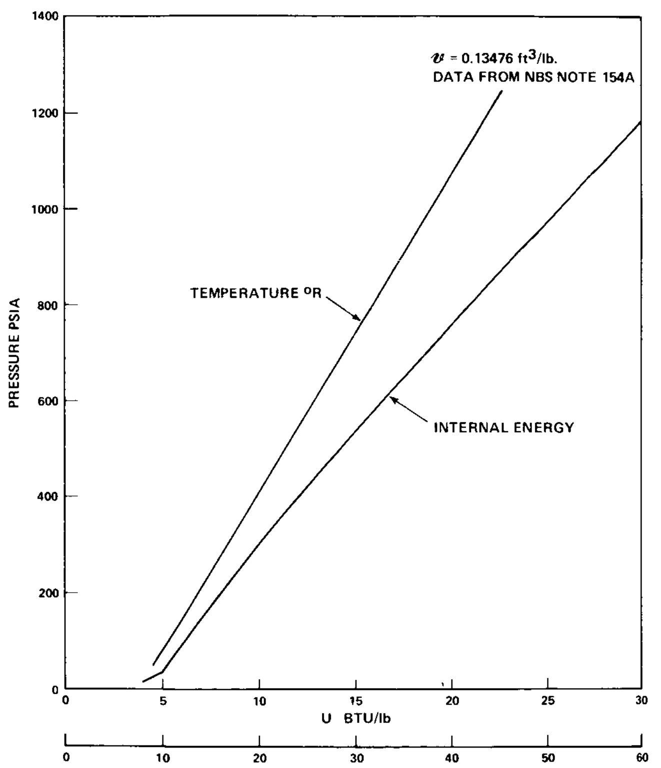


Figure 2.11 *Internal energy and temperature of He versus pressure in a closed Dewar.*

Refrigerated Cryogenic Storage

Another method for reducing weight and volume of the helium storage would be pressurized storage at liquid oxygen temperature (-297° F); at 1250 psi and 100 atm, the density is ~4.20 lb/ft^3. Using the same Dewar as designed for the supercritical system, which was 84.5 ft^3 in volume, this system would contain [(4.20 X 1250)/0.01034] = 50,600 SCF, and that available above 1000 psi would be ~46,000 SCF. Assuming that the delivery system would be no greater in weight than the one used in the supercritical system, we would obtain a ratio of 3.26 SCF/lb of metal in the system.

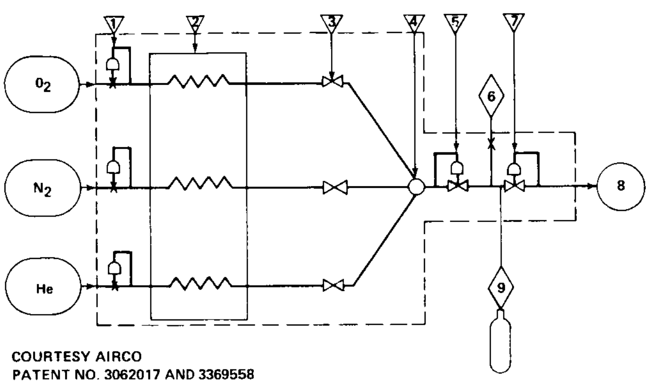
This system is promising in that the gas can be converted to a usable form, as required, and will not require helium transfer relative to thermal insulation characteristics. The use of liquid oxygen as a refrigerant appears logical in that the liquid produced and stored can be converted to gas to supply the system oxygen requirements.

The U.S. Navy currently uses cryogenic processes in small Joule-Thompson type liquefiers installed aboard aircraft carriers to generate breathing oxygen for fliers. The cryogenic refrigerated storage concept could be developed on the basis of experience and available technology.

GAS MIXING SYSTEMS

There are three basic methods of preparing breathing gas mixtures. The first two are mixing by weight and mixing by partial pressures. These are batch processes, and they introduce significant error in mix ratios because of deviation from ideal gas laws (ref. 1). Diffusion of oxygen into helium is a slow process; in some instances, it takes several days to obtain stabilized concentrations when the storage vessels are large.

The third technique, normally required for sustained large-scale diving operations, is a continuous flow method that consists of metering and controlling separate streams of oxygen, helium, and air or nitrogen and mixing them at high turbulence downstream from the metering system. To be effective this method requires a simple, easy-to-operate mixing system and a reliable analyzer to detect malfunctions quickly enough to permit adjustments to the gas mixture. The gas mixture may be fed directly to the diver through hose and regulators, introduced into a chamber such as a habitat or personnel transfer capsule, or recompressed and stored for later use.



COURTESY AIRCO
PATENT NO. 3062017 AND 3369558

1 REGULATOR
2 HEAT EXCHANGES
3 METERING VALVES
4 MIXING CHAMBER
5 REGULATOR
6 ANALYZER
7 REGULATOR
8 SUPPLY TO DIVERS
9 ACCUMULATOR

Figure 2.12 *AIRCO gas mixing system.*

Figure 2.12 shows the principles of the system, an Airco Mixmaker (TM), that is presently in use at the Navy Experimental Diving Unit. Stored, pure gases are supplied to the system at approximately 1100 psi through a regulator (1). At a constant, regulated pressure, the gases are passed through a heat exchanger (2) to reach a preset constant temperature. The system utilizes sonic flow characteristics through calibrated metering valves (3). The gases are mixed in a turbulent mixing chamber (4) and then sent through a regulator controlling flow-meter-outlet pressure at ~750 psi. The gas is sampled by bleeding from the main flow and routed to a gas chromatograph or other recording gas analyzer (6). The main gas stream passes through a final regulator (7) to be supplied directly to the divers (8). An accumulator (9) should be added to prevent high concentrations of oxygen from reaching the divers in the event of system malfunction. The mixed gas could be fed to storage cylinders or into a high-pressure diaphragm compressor for additional pressurization prior to storage.

The accuracy of mixing claimed for this system is as follows:

Amount of oxygen in mixture	*Precision of oxygen content*
0 - 10%	±0.15% O_2
10 - 15%	±0.25% O_2
15 - 100%	±0.50% O_2

For example, mixed gas prepared at the 9 percent setting would contain between 8.85 and 9.15 percent of pure oxygen.

Continuous-flow breathing-gas mixture systems, such as the system described above, can be fed to high-pressure compressors for filling UBA tanks or compressed-gas storage banks, as desired.

The oxygen content of the mixture would depend on the type of breathing apparatus to be used and the range of diving depths anticipated.

The Airco Mixmaker represents a fairly recent concept in gas mixing for underwater breathing applications. Since the only outside resources required are pure gas and electrical power, both binary and ternary mixtures of any predetermined requirement can be mixed on site, a significant advantage over "batch basis" mixing. Another version of a gas mixing system is shown in figure 2.13. This system uses calibrated turbine-type flowmeters and two-stage motor-operated needle valves.

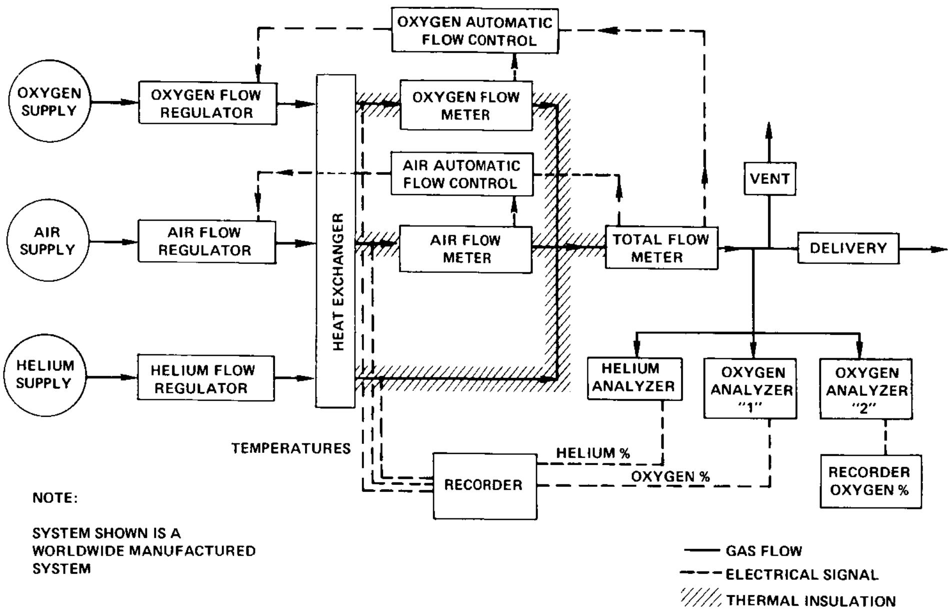


Figure 2.13. *Worldwide gas mixing system.*

GAS TRANSFER SYSTEMS

Transfer systems consisting of suitable noncontaminating compressors are desirable for helium, oxygen, and mixed gas systems. They enhance the performance ratio of SCF of helium available per pound of metal, but their operation requires a relatively high inlet pressure, as much as 200 to 400 psig for some of the smaller units. Figure 2.14 illustrates a transfer system utilizing an A5C250 compressor.

Application of these pumps in a system requires some knowledge of their performance characteristics. The only known parameters that can be applied are the displacement volume and rpm, from which the displacement per unit time and the flow capacity as related to the inlet pressure, outlet pressure, volumetric efficiency, and real gas properties can be obtained. The volumetric efficiency can be established theoretically if clearance volume is known, but more frequently, it is determined experimentally for each type of compressor. The volumetric efficiency for one model of a diaphragm type compressor is shown in figure 2.15. When the displacement and the volumetric efficiency are known, a simple computation relating the flow through the compressor with varying upstream-downstream pressure conditions, which are normally present in gas transfer operations, can be performed.

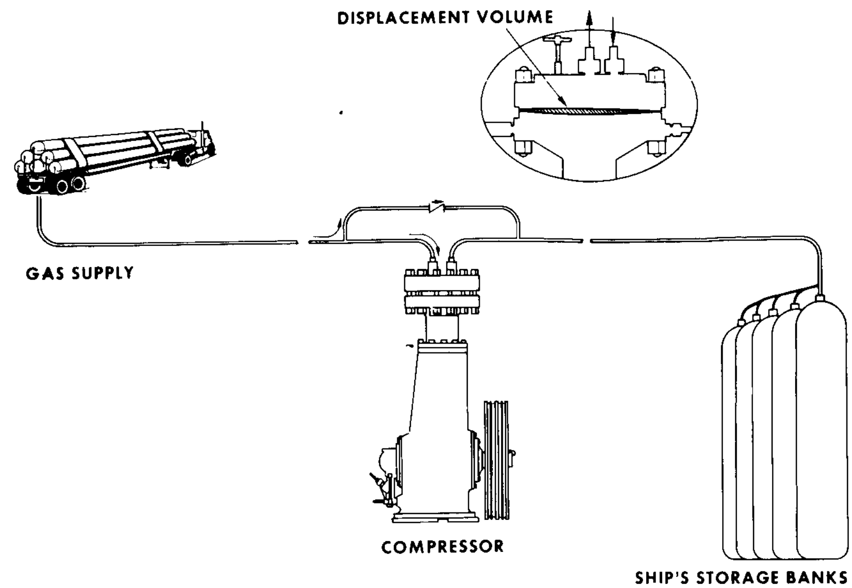


Figure 2.14 *A5C250 compressor unit.*

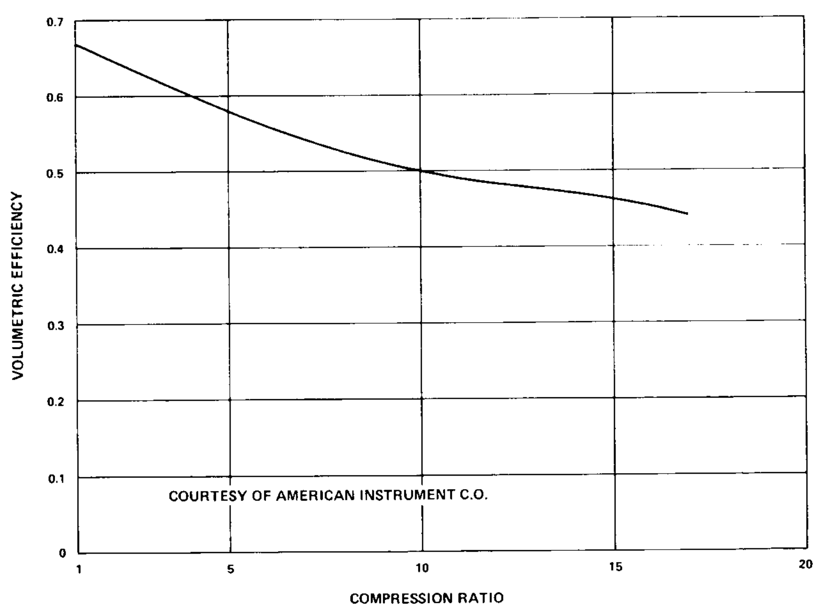


Figure 2.15 *Volumetric efficiency curve A5C250 compressor.*

A program was developed (appendix D), in which the data input permits variation in the input parameters (table 2.3). The program progressively reduces the pressure in the supply volume relative to the compressor displacement as affected by clearance, which is related to downstream pressure. It follows conventional compressor principles where a lb_{in} is a lb_{out} but takes into account the effect of the upstream-downstream condition on the flow capacity.

Table 2.3 *Input data constants for calculating He transfer time*

INPUT DATA

VOLUME OF ON BOARD STORAGE BANK	24.0 CU FEET
DESIGN PRESSURE OF STORAGE BANK	3000.0 PSIG
MINIMUM PRESSURE OF STORAGE BANK BEFORE PUMPING MAY BE INITIATED	200.0 PSIG
VOLUME OF SUPPLY BANK (100 BOTTLES)	60.0 CU FEET
INITIAL DELIVERY PRESSURE OF SUPPLY BANK	3000.0 PSIG
MINIMUM (RETURN) PRESSURE OF SUPPLY BANK	200.0 PSIG
PUMP CLEARANCE VOLUME	5.0 PERCENT
DURATION OF ONE PUMPING CYCLE	9.0 MINUTE(S)
VOLUME DISPLACED BY PUMP IN ONE MINUTE	0.6 CU FEET
POLYTROPIC PROCESS EXPONENT	1.6
TEMPERATURE OF GAS (ASSUMED CONSTANT)	70.0 DEG-F
HELIUM GAS CONSTANT (R)	386.3 FT-LBF/LBM-R

See Appendix D for the complete program and data concerning calculation of helium transfer time.

Although in our application of the program the polytropic exponent was near that of conventional compressors, in practice it more nearly approaches isothermal compression. Results obtained have provided transfer time for various shipboard applications, establishing constraints on time-related application of the compressor (e.g., the transfer of helium from a tube trailer into the nearby gas storage system).

COMPRESSED AIR CONSIDERATIONS

Although compressed air has limited application in DDS, it is the most common breathing gas used by divers.

In deep diving systems compressed air is only for pressurizing the enclosures to an equivalent pressure to 14 ft of seawater to increase the oxygen partial pressure to 228 mm Hg so that the monitoring instrumentation can be zeroed and performance can be verified. Compressed air is used to support conventional surface-supplied systems and the more common scuba gear.

Purity Standards and Monitoring Techniques

Current purity standards for breathing air are:

Oxygen	20 to 22 percent by volume
Carbon dioxide	300 to 500 ppm (0.03 to 0.05 percent) by volume
Carbon monoxide	20 ppm maximum
Oil, mist, and vapor	5 mg/m^3 maximum
Solid and liquid particles	not detectable except as noted above under oil, mist, and vapor
Odor	not objectionable

Efforts to provide appropriate equipment for meeting these standards have been extensive. Filter testing at both the manufacturer's facility and another laboratory, together with a short-term test on one of the ARS-type ships, has verified the performance of an oil- and particulate-removal filter system. Procurement has been initiated for sufficient units to supply each existing salvage ship (ARS) and submarine rescue ship (ASR) with a portable unit, and an adequate number was included for salvage equipment pools, for supporting HCU and ATF surface-supplied diving.

Other projects include definition of compressor lubricating oils and their additives, with recommendations to exclude the use of oils containing phosphate esters. The commonly used 2190 TEP will be replaced with a 2135 TH type oil.

Proposed projects for monitoring techniques that will permit air sampling from the shipboard systems are being reviewed. These projects fall into two categories. The first is a technique for adapting coal dust monitoring equipment, under development as required by a recently established public law, for use in determining, on a periodic basis, the oil and particulate matter in diver air systems. This work involves the development of sampling techniques and adaptation of the coal dust sampler cassette for the sampling of air in diver breathing systems.

Currently under study are selective permeable membranes, incorporated into cassettes, that collect oil aerosols and particulate matter as the sample air passes through them. Once calibrated to provide representative quantities, these membranes will indicate the quantities of these contaminants in an air stream. The contaminant levels established for the coal dust monitoring equipment are strikingly similar to diver system requirements: 2 mg/m^3 and 5 mg/m^3, respectively.

A second category comprises techniques for establishing the gaseous contaminants. A proposal in this area is under consideration that would refine current practice and hopefully provide acceptable techniques for periodically analyzing the air from divers' breathing gas systems.

Systems cleaning presents a major problem particularly in existing systems that do not permit in-place cleaning. Future installations, where practicable, will permit in-place cleaning.

CONCLUSION

The analytical approach to the design of compressed gas systems for supporting deep diving systems offers a method of effectively determining gas requirements and storage system definition. Although shipboard installations are not normally weight sensitive, the magnitude of these installations requires some optimization to reduce the weight.

Gas mixing systems also appear essential to provide the low concentration mixtures within the converging tolerance range dictated by applications to ever-increasing depths.

Time-related use of gas together with the performance of the gas transfer system is another significant consideration to ensure transfer within a reasonable time frame for systems application.

REFERENCES

1. U.S. Navy Diving Gas Manual, Oct. 1, 1969. U.S. Navy Supervisor of Diving Research Report 3-69.
2. Journal of Chemical Engineering Data, vol. 5, no. 1, Jan. 1960.
3. Anon.: Flask, Compressed Gas and End Plugs for Air, Oxygen, and Nitrogen. Military Spec. Mil-F-22606B (Ships).

APPENDIX A

PROGRAM - VIRIAL

```
PRØGRAM   VIRIAL

00100 READ R,T,T1,T2,T3,T4,T5,T9,B,B1,B2,B3,B4,B5
00110 DIM A(7),A1(7),A2(7),A3(7),A4(7),A5(7),A6(7)
00120 FØR C = 1 TØ 7
00130 READ A(C)
00140 NEXT C
00150 FØR C1 = 1 TØ 7
00160 READ A1(C1)
00170 NEXT C1
00180 FØR C2 = 1 TØ 7
00190 READ A2(C2)
00200 NEXT C2
00210 FØR C3 = 1 TØ 7
00220 READ A3(C3)
00230 NEXT C3
00240 FØR C4 = 1 TØ 7
00250 READ A4(C4)
00260 NEXT C4
00270 FØR C5 = 1 TØ 7
00280 READ A5(C5)
00290 NEXT C5
00300 FØR C6 = 1 TØ 7
00310 READ A6(C6)
00320 NEXT C6
00330 PRINT"TEMPERATURE DEG F   "T
00340 GØSUB 01380
00350 PRINT
00360 FØR I = 1 TØ 7
00370 LET P = A6(I)
00380 LET D = A(I)
00390 LET D1 = P/((1+B*P)*R*(T9+T))
00400 LET D2 = D1*1728
00410 LET V = ((D2-D)/D)*100
00420 LET V1 = 100*V
00430 LET V2 = INT(V1*10↑3 + .5)/10↑3
00440 LET V3 = V2/100
00450 PRINT TAB(1),P,TAB(13),D,TAB(30),D2,TAB(52),V3
00460 NEXT I
00470 PRINT
00480 PRINT
00490 PRINT"TEMPERATURE DEG F"T1
00500 GØ SUB 01380
00510 PRINT
00520 FØR I1 = 1 TØ 7
00530 LET P = A6(I1)
00540 LET D = A1(I1)
00550 LET D1 = P/((1+B1*P)*R*(T9+T1))
00560 LET D2 = D1*1728
00570 LET V = ((D2-D)/D)*100
00580 LET V1 = 100*V
00590 LET V2 = INT(V1*10↑3 + .5)/10↑3
00600 LET V3 = V2/10C
00610 PRINT TAB(Q),P,TAB(13),D,TAB(30,,D2,TAB(52),V3
00620 NEXT I1
00630 PRINT
00640 PRINT
00650 PRINT"TEMPERATURE DEG F"T2
00660 GØSUB 01380
00670 PRINT
00680 FØR I2 = 1 TØ 7
00690 LET P = A6(I2)
00700 LET D = A2(I2)
00710 LET D1 = P/((1+B2*P)*R*(T9+T2))
00720 LET D2 = D1*1728
00730 LET V = ((D2-D)/D)*100
00740 LET V1 = 100*V
00750 LET V2 = INT(V1*10↑3 +.5)/10↑3
00760 LET V3 = V2/100
00770 PRINT TAB(1),P,TAB(13),D,TAB(30),D2,TAB(52),V3
00780 NEXT I2
00790 PRINT
00800 PRINT
00810 PRINT"TEMPERATURE DEG F"T3
00820 GØ SUB 01380
00830 PRINT
00840 FØR I3 = 1 TØ 7
00850 LET P = A6(I3)
00860 LET D = A3(I3)
00870 LET D1 = P/((1+B3*P)*R*(T9+T3))
00880 LET D2 = D1*1728
00890 LET V = ((D2-D)/D)*100
00900 LET V1 = 100*V
00910 LET V2 = INT(V1*10↑3 + .5)/10↑3
00920 LET V3 = V2/100
00930 PRINT TAB(1),P,TAB(13),D,TAB(30),D2,TAB(52),V3
00940 NEXT I3
00950 PRINT
00960 PRINT
00970 PRINT"TEMPERATURE DEG F"T4
00980 GØSUB 01380
00990 PRINT
01000 FØR I4 = 1 TØ 7
01010 LET P = A6(I4)
01020 LET D = A4(I4)
01030 LET D1 = P/((1+B4*P)*R*(T9+T4))
01040 LET D2 = D1*1728
01050 LET V = ((D2-D)/D)*100
01060 LET V1 = 100*V
01070 LET V2 = INT(V1*10↑3 + .5)/10↑3
01080 LET V3 = V2/100
01090 PRINT TAB(1),P,TAB(13),D,TAB(30),D2,TAB(52),V3
01100 NEXT I4
01110 PRINT
01120 PRINT
01130 PRINT"TEMPERATURE DEG F"T5
01140 GØSUB 01380
01150 PRINT
01160 FØR I5 = 1 TØ 7
01170 LET P = A6(I5)
01180 LET D = A5(I5)
01190 LET D1 = P/((1+B5*P)*R*(T9+T5))
01200 LET D2 = D1*1728
01210 LET V = ((D2-D)/D)*100
01220 LET V1 = 100*V
01230 LET V2 = INT(V1*10↑3 +.5)/10↑3
01240 LET V3 = V2/100
01250 PRINT TAB(1),P,TAB(13),D,TAB(30),D2,TAB(52),V3
01260 IF I5 = 7 THEN 01470
01270 NEXT I5
01280 DATA 4636, 30, 50, 70, 90, 110, 130, 459.6
01290 DATA 3.4480E-5, 3.29277E-5, 3.16830E-5, 3.02923E-5, 2.90253E-5
01300 DATA 2.78820E-5
01310 DATA .01119, .37416, .73545, 1.08472, 1.4227, 1.7501, 2.0676
01320 DATA .01075, .35975, .70764, 1.04443, 1.3708, 1.6873, 1.9945
01330 DATA .01034, .34641, .68186, 1.00703, 1.3225, 1.6288, 1.9265
01340 DATA .00997, .33402, .65790,  .97223, 1.2775, 1.5743, 1.8631
01350 DATA .00962, .32249, .63557,  .93976, 1.2356, 1.5234, 1.8037
01360 DATA .00929, .31174, .61471,  .90941, 1.1963, 1.4756, 1.7480
01370 DATA 14.7, 500, 1000, 1500, 2000, 2500, 3000
01380 PRINT
01390 PRINT TAB(15),"USN DIVING",TAB(29),"VIRIAL CØEFF.",
01400 PRINT TAB(51),"DIFFERENCE"
01410 PRINT"PRESSURE",TAB(15),"GAS MANUAL",TAB(30),"CØMPUTATIØN",
01420 PRINT TAB(53),"PERCENT"
01430 PRINT TAB(16),"DENSITY",TAB(32),"DENSITY"
01440 PRINT TAB(2),"PSIA",TAB(16),"LBS/FT3",TAB(32),"LBS/FT3",
01450 PRINT
01460 RETURN
01470 END
```

PROGRAM VIRIAL - OUTPUT DATA

PRØGRAM VIRIAL

TEMPERATURE DEG F 30

PRESSURE PSIA	USN DIVING GAS MANUAL DENSITY LBS/FT3	VIRIAL CØEFF COMPUTATIØN DENSITY LBS/FT3	DIFFERENCE PERCENT
14.7	.01119	1.11855 E-2	-.04004
500	.37416	.374201	.01108
1000	.73545	.735931	.06533
1500	1.08472	1.0858	.09961
2000	1.4227	1.42439	.11845
2500	1.7501	1.75222	.12125
3000	2.0676	2.06981	.10711

TEMPERATURE DEG F 50

PRESSURE PSIA	USN DIVING GAS MANUAL DENSITY LBS/FT3	VIRIAL CØEFF. CØMPUTATIØN DENSITY LBS/FT3	DIFFERENCE PERCENT
14.7	.01075	1.07468 E-2	-.03002
500	.35975	.35979	.01109
1000	.70764	.70811	.06647
1500	1.04443	1.0455	.10258
2000	1.3708	1.37247	.12177
2500	1.6873	1.68949	.12977
3000	1.9945	1.99701	.12583

TEMPERATURE DEG F 70

PRESSURE PSIA	USN DIVING GAS MANUAL DENSITY LBS/FT3	VIRIAL CØEFF. CØMPUTATIØN DENSITY LBS/FT3	DIFFERENCE PERCENT
14.7	.01034	1.03411 E-2	.0108
500	.34641	.346415	.00137
1000	.68186	.682191	.04856
1500	1.00703	1.00781	.07763
2000	1.3225	1.32373	.09304
2500	1.6288	1.63037	.09667
3000	1.9265	1.92815	.08547

TEMPERATURE DEG F 90

PRESSURE PSIA	USN DIVING GAS MANUAL DENSITY LBS/FT3	VIRIAL CØEFF. CØMPUTATIØN DENSITY LBS/FT3	DIFFERENCE PERCENT
14.7	00997	9.96501 E-3	-.05009
500	.33402	.334037	.00519
1000	.6579	.658253	.05372
1500	.97223	.973075	.08693
2000	1.2775	1.2789	.10998
2500	1.5743	1.57612	.11578
3000	1.8631	1.86509	.10665

TEMPERATURE DEG F 110

PRESSURE PSIA	USN DIVING GAS MANUAL DENSITY LBS/FT3	VIRIAL CØEFF. CØMPUTATIØN DENSITY LBS/FT3	DIFFERENCE PERCENT
14.7	.00962	9.61529 E-3	-.04896
500	.32249	.32251	.00613
1000	.63557	.635923	.05548
1500	.93976	.940618	.09131
2000	1.2356	1.23695	.10966
2500	1.5234	1.52527	.12291
3000	1.8037	1.80589	.12151

TEMPERATURE DEG F 130

PRESSURE PSIA	USN DIVING GAS MANUAL DENSITY LBS/FT3	VIRIAL CØEFF. CØMPUTATIØN DENSITY LBS/FT3	DIFFERENCE PERCENT
14.7	.00929	9.28928 E-3	-.00772
500	.31174	.311745	.00176
1000	.61471	.615035	.05281
1500	.90941	.910207	.08764
2000	1.1963	1.19758	.10733
2500	1.4756	1.47747	.12676
3000	1.748	1.75016	.12332

APPENDIX B

PROGRAM - HELIUM CAPACITY

```
10 PRINT"    TOTAL HELIUM CAPACITY OF FLASKS AT RATED DESIGN PRESSURE"
20 PRINT"                     CONSIDERING VARIOUS DIAMETERS"
30 PRINT
40 DIM V3(4,9),W(4,9),C(4,9),C1(4,9),S1(9)
50 DIM C2(4,9)
60 FOR A = 1 TO 9
70 READ S1(A)
80 NEXT A
90 LET S2 = .31851
100 FOR D0 = 18 TO 24 STEP 2
110 LET K = (D0/2)-8
120 LET L = 92
130 LET L1 = 92 - D0
140 LET R0 = D0/2
150 LET V = (4/3)*3.1416*R0↑3 + L1*3.1416*R0↑2
160 LET S = 0.67*110000
170 PRINT
180 PRINT"  FLASK DIAMETER",D0" INCHES"
190 PRINT
200 PRINT TAB(7),"DESIGN",TAB(20),"WALL",TAB(34),"INTERNAL"
210 PRINT TAB(7),"PRESS.",TAB(18),"THICKNESS",TAB(35),"VOLUME",
220 PRINT TAB(50),"WEIGHT"
230 PRINT TAB(9),"PSI",TAB(20),"INCH",TAB(37),"FT3",TAB(51),"LBS"
240 PRINT
250 FOR I = 1 TO 9
260 LET P = 1400 + I*400
270 LET P1 = (5/3)*P
280 LET D1 = D0*((S - 1.3*P1)/(S + 0.4*P1))↑0.5
290 LET D2 = D1 - 2*0.065
300 LET R1 = D2/2
310 LET V1 = (4/3)*3.1416*R1↑3 + L1*3.1416*R1↑2
320 LET V3(K,I) = V1/1728
330 LET V2 = (V-V1)/1728
340 LET W(K,I) = V2*485
350 LET T = (D0-D2)/2
360 LET C(K,I) = V3(K,I)*(S1(I) - S2)/0.01034
370 LET C1(K,I) = C(K,I)/W(K,I)
380 LET C2(K,I) = V3(K,I)*(S1(I)/0.01034)
390 PRINT P,T,V3(K,I),W(K,I)
400 NEXT I
410 NEXT D0
417 PRINT
418 PRINT
419 PRINT
420 PRINT"    TOTAL HELIUM CAPACITY OF FLASKS AT RATED DESIGN PRESS."
430 PRINT"         - AND - HELIUM AVAILABLE TO AN EQUILIBRIUM DEPTH"
440 PRINT"               EQUIVALENT TO 1000 FEET OF SEA-WATER"
450 PRINT
460 PRINT
470 FOR K3 = 1 TO 4
480 LET D0 = 16 + 2*K3
490 PRINT
500 PRINT"  FLASK DIAMETER",D0" INCHES"
510 PRINT
520 PRINT TAB(7),"DESIGN",TAB(20),"TOTAL",TAB(34),"AVAIL. HE",
530 PRINT TAB(48),"SCF HELIUM"
540 PRINT TAB(7),"PRESS.",TAB(19),"STORAGE",TAB(33),"FOR 1000 FT",
550 PRINT TAB(48),"AVAIL. PER"
560 PRINT TAB(8),"PSI",TAB(21),"SCF",TAB(33),"DIVE - SCF",
562 PRINT TAB(48),"LB OF METAL"
565 PRINT
570 FOR I1 = 1 TO 9
580 LET P = 1400 + I1*400
590 PRINT P,C2(K3,I1),C(K3,I1),C1(K3,I1)
600 NEXT I1
610 NEXT K3
620 DATA 1.206632, 1.455111, 1.697805, 1.935114, 2.167208, 2.394232
630 DATA 2.616470, 2.834094, 3.047276
640 END
```

OUTPUT DATA

TOTAL HELIUM CAPACITY OF FLASKS AT RATED DESIGN PRESS.
- AND - HELIUM AVAILABLE TO AN EQUILIBRIUM DEPTH
EQUIVALENT TO 1000 FEET OF SEA-WATER

FLASK DIAMETER 18 INCHES

DESIGN PRESS. PSI	TOTAL STORAGE SCF	AVAIL. HE FOR 1000 FT DIVE - SCF	SCF HELIUM AVAIL. PER LB OF METAL
1800	1348.811	992.7708	1.85044
2200	1598.746	1248.796	1.974715
2600	1833.215	1489.302	2.047285
3000	2053.086	1715.158	2.087352
3400	2258.954	1926.96	2.105693
3800	2451.367	2125.256	2.108922
4200	2630.996	2310.717	2.101459
4600	2798.374	2483.878	2.086196
5000	2954.016	2645.254	2.065158

FLASK DIAMETER 20 INCHES

DESIGN PRESS. PSI	TOTAL STORAGE SCF	AVAIL. HE FOR 1000 FT DIVE - SCF	SCF HELIUM AVAIL. PER LB OF METAL
1800	1653.805	1217.257	1.870051
2200	1960.024	1530.993	1.990134
2600	2247.21	1825.631	2.059095
3000	2516.436	2102.243	2.096135
3400	2768.436	2361.565	2.111953
3800	3003.887	2604.273	2.113074
4200	3223.618	2831.198	2.103843
4600	3428.286	3042.998	2.087091
5000	3618.529	3240.31	2.064793

FLASK DIAMETER 22 INCHES

DESIGN PRESS. PSI	TOTAL STORAGE SCF	AVAIL. HE FOR 1000 FT DIVE - SCF	SCF HELIUM AVAIL. PER LB OF METAL
1800	1986.726	1462.298	1.883806
2200	2354.299	1838.965	2.000091
2600	2698.922	2192.602	2.06586
3000	3021.893	2524.504	2.100271
3400	3324.098	2835.562	2.113927
3800	3606.36	3126.598	2.113264
4200	3869.679	3398.613	2.102553
4600	4114.853	3652.405	2.084569
5000	4342.652	3888.746	2.061239

FLASK DIAMETER 24 INCHES

DESIGN PRESS. PSI	TOTAL STORAGE SCF	AVAIL. HE FOR 1000 FT DIVE - SCF	SCF HELIUM AVAIL. PER LB OF METAL
1800	2346.727	1727.271	1.892969
2200	2780.553	2171.916	2.005791
2600	3187.166	2599.251	2.068714
3000	3568.108	2980.815	2.100817
3400	3924.436	3347.67	2.112598
3800	4257.129	3690.793	2.110407
4200	4567.376	4011.377	2.098443
4600	4856.127	4310.37	2.079425
5000	5124.298	4588.692	2.055241

OUTPUT DATA

TOTAL HELIUM CAPACITY OF FLASKS AT RATED DESIGN PRESSURE CONSIDERING VARIOUS DIAMETERS

FLASK DIAMETER 18 INCHES

DESIGN PRESS. PSI	WALL THICKNESS INCH	INTERNAL VOLUME FT3	WEIGHT LBS
1800	.3768101	11.55838	536.5054
2200	.4462458	11.36067	632.3931
2600	.5157485	11.16467	727.452
3000	.5853251	10.97037	821.691
3400	.6549829	10.77773	915.1192
3800	.7247291	10.58675	1007.745
4200	.7945708	10.3974	1099.578
4600	.8645161	10.20968	1190.625
5000	.9345727	10.02355	1280.896

FLASK DIAMETER 20 INCHES

DESIGN PRESS. PSI	WALL THICKNESS INCH	INTERNAL VOLUME FT3	WEIGHT LBS
1800	.4114556	14.17197	650.9219
2200	.4886065	13.92791	769.2914
2600	.5658317	13.68599	886.6183
3000	.643139	13.44621	1002.914
3400	.7205366	13.20853	1118.19
3800	.7980322	12.97292	1232.457
4200	.8756342	12.73938	1345.727
4600	.9533513	12.50787	1458.009
5000	1.031192	12.27837	1569.315

FLASK DIAMETER 22 INCHES

DESIGN PRESS. PSI	WALL THICKNESS INCH	INTERNAL VOLUME FT3	WEIGHT LBS
1800	.4461012	17.02487	776.2464
2200	.530967	16.72962	919.4408
2600	.6159148	16.43702	1061.351
3000	.7009529	16.14704	1201.99
3400	.7860903	15.85966	1341.372
3800	.8713354	15.57483	1479.512
4200	.9566977	15.29254	1616.422
4600	1.042186	15.01276	1752.116
5000	1.127811	14.73546	1886.606

FLASK DIAMETER 24 INCHES

DESIGN PRESS. PSI	WALL THICKNESS INCH	INTERNAL VOLUME FT3	WEIGHT LBS
1800	.4807467	20.10983	912.4662
2200	.5733277	19.75857	1082.823
2600	.665998	19.41053	1251.623
3000	.7587668	19.06567	1418.884
3400	.8516439	18 72394	1584.622
3800	9446386	18.38532	1748.854
4200	1.037761	18.04976	1911.597
4600	1.131021	17.71725	2072.866
5000	1.22443	17.38774	2232.678

APPENDIX C

PROGRAM - HELIUM AVAILABLE FOR SATURATION DIVING MISSION

```
10 READ U,V,Y,D
15 LET P = 0.44444*D
20 LET P1 = 0.44444*D - 0.5*0.44444
25 LET P2 = 3000
30 LET Z = 1 + U*P
35 LET Z1 = 1 + V*P
40 LET Z2 = 1 + Y*P
45 LET Z3 = 1 + U*P1
50 LET Z4 = 1 + V*P1
55 LET Z5 = 1 + Y*P1
60 LET Z6 = 1 + U*P2
65 LET Z7 = 1 + V*P2
70 LET Z8 = 1 + Y*P2
75 LET Z9 = 1 + V*3814.7
80 LET K = 4.0026*144/(1546*495)
85 LET K1 = 4.0026*144/(1546*548)
90 LET K2 = 4.0026*144/(1546*570)
95 LET W = K*P/Z
100 LET W1 = K*P1/Z3
105 LET W2 = K*P2/Z6
110 LET W3 = K1*P/Z1
115 LET W4 = K1*P1/Z4
120 LET W5 = K1*P2/Z7
125 LET W6 = K2*P/Z2
130 LET W7 = K2*P1/Z5
135 LET W8 = K2*P2/Z8
140 LET W9 = K1*3814.7/Z9
145 LET R1 = 1000*W3/0.01034
150 LET R2 = 235*W3/0.01034
155 LET R3 = (227 + 29)*W3/0.01034
160 LET A = 153860.5 - R1 - R2 - R3
165 LET H = 1 - (1.2/((0.44444*D + 14.7)/14.7))
170 LET M = H*2*16.88*W9/0.01034
175 LET M1 = M
180 LET M2 = M
185 LET M3 = HD 4*6*W5/0.01034
190 LET M4 = 5*6*W5/0.01034
195 LET A1 = A - M - M1 - M2 - M3 - M4
200 LET C = 235*W3/0.01034
205 LET C1 = 765*W3/0.01034
210 LET C2 = 227*W3/0.01034
213 LET A2 = A1 - C - C1 - C2
215 LET C3 = 2*16*W3/0.01034
220 LET C4 = 2 *13*W3/0.01034
225 LET C5 = 4*3*W3/0.01034
230 LET C6 = 2*227*(W3 - W6)/0.01034
232 LET C7 = 2*16*W/0.01034
235 LET C8 = (476.43*1.5)*2*2
240 LET C9 = 0.5*3*W3/0.01034
245 LET L = 24*1000*(W3 - W4)/0.01034
250 LET L1 = 24*227*(W3 - W4)/0.01034
255 LET L2 = L + L1
257 LET R4 = C3 + C4 + C5 + C9
260 LET B = C3 + C4 + C5 + C6 + C7 + C8 + C9
265 FOR X = 1 TO 10 STEP 1
267 LET L3 = X*L2
268 LET R5 = X*R4
270 LET A3 = A2 - X)(B + L2)
280 PRINT A;A1;A2;A3;L3;R5
290 NEXT X
300 DATA 3.3979E-5,3.0431E-5,2.9025E-5,850
305 PRINT
306 PRINT
307 PRI LT
308 PRINT "DEFINITION OF SYMBOLS"
309 PRINT
310 PRINT "PRESSURE EQUIV. TO 850FT. S.W.                PSIA" P
311 PRINT "                 TO 850FT. S.W. MINUS 0.5FT.  PSIA" P1
312 PRINT "PTC FLASK WP P2 = " P2
313 PRINT "COMPRESSIBILITY FOR P  AT  35 DEGREES F, Z =" Z
314 PRI LT "                   P  AT  88 DEGREES F, Z1 =" Z1
315 PRINT "                    P  AT 110 DEGREES F, Z2 =" Z2
316 PRINT "                    P1 AT  35 DEGREES F, Z3 =" Z3
317 PRINT "                    P1 AT  88 DEGREES F, Z4 =" Z4
318 PRINT "                    P1 AT 110 DEGREES F, Z5 =" Z5
319 PRINT "                    P2 AT  35 DEGREES F, Z6 =" Z6
320 PRINT "                    P2 AT  88 DEGREES F, Z7 =" Z7
321 PRINT "                    P2 AT 110 DEGREES F, Z8 =" Z8
322 PRINT "                3814.7 AT  88 DEGREES F, Z9 =" Z9
323 PRINT "HELIUM DENSITY AT      P  AND  35F, LB/FT3 W  =" W
324 PRINT "                       P1 AND  35F, LB/FT3 W1 =" W1
325 PRINT "                       P2 AND  35F, LB/FT3 W2 =" W2
326 PRINT "                       P  AND  88F, LB/FT3 W3 =" W3
327 PRI LT "                      P1 AND  88F, LB/FT3 W4 =" W4
328 PRINT "                       P2 ALD  88F, LB/FT3 W5 =" W5
329 PRINT "                       P  AND 110F, LB/FT3 W6 =" W6
330 PRINT "                       P1 AND 110F, LB/FT3 W7 =" W7
331 PRINT "                       P2 AND 110F, LB/FT3 W8 =" W8
332 PRINT "                   3814.7 AND  88F, LB/FT3 W9 =" W9
333 PRINT "RESERVE FOR HYPERBARIC TREATMENT IN DDC, SCF" R1
334 PRINT "RESERVE FOR OUTER LOCK OPERATION ONCE,   SCF" R2
335 PRINT "RESERVE FOR PTC MAINTENANCE ONCE,        SCF" R3
336 PRILT "*******QUA ITITY AVAILABLE FOR DIVING MISSION SCF"A
337 PRINT "HELIUM FRACTION IN MIXED GAS" H
338 PRINT "HELIUM FOR SHIP'S MIXED GAS BANK PER BANK SCF" M
339 PRINT " HELIUM FOR PTC MIXED GAS FLASKS SCF" M3
340 PRINT " HELIUM FOR PTC HELIUM FLASKS SCF" M4
341 PRINT "*******QUANTITY AVAILABLE FOR DIVING MISSION SCF"A1
342 PRINT "HELIUM FOR PRESSURIZATION DDC OUTER LOCK SCF" C
343 PRINT "HELIUM FOR PRESSURIZATION DDC INNER LOCK SCF" C1
344 PRINT "HELIUM FOR PTC PRESSURIZATION SCF" C2
345 PRINT "*******QUANTITY AVAILABLE FOR DAILY OPERATIONS SCF"A2
346 PRINT " DAILY OPERATIONS "
347 PRINT "DDC TRUNK PRESS. TWICE DAILY SCF" C3
348 PRI LT "PTC TRUNK PRESS. TWICE DAILY SCF" C4
349 PRINT " MEDICAL LOCK FOUR DAI IY SCF" C5
350 PRINT " PTC DELTA T EQUALIZATION,TWICE DAILY SCF" C6
351 PRINT"PTC TRUNK BLOW AT DEPTH TWICE DAILY SCF" C7
352 PRINT " DIVERS USE WITH 0.008 IL.0RIFICE MARI 11 SCF" C8
353 PRINT " LOSS IN PTC SCRUBBER CHANGE ONCE EVERY TWO DAYS SCF" C9
354 PRINT "DAILY LEAKAGE DDC, INNER & OUTER LOCK     SCF" L
355 PRI LT "DAILY LEAKAGE PTC,                       SCF" L1
356 PRINT "TOTAL DAILY LEAKAGE DDC A ID PTC          SCF" L2
357 PRINT "HELIUM USE DAILY FOR DIVING OPS        SCF" B
358 PRINT "HELIUM RECOVERABLE DURING DIVING OPS  SCF/DAY" R4
360 END
```

DATA

COLUMNS:

- A AVAILABLE TO OPERATE SYSTEM
- B AVAILABLE AFTER CHARGING PTC FLASKS AND SHIP'S MIXED GAS FLASKS
- C AVAILABLE AFTER ENCLOSURE PRESSURIZATION
- D AVAILABLE AFTER DAILY OPERATION
- E CUMULATIVE DDC AND PTC LEAKAGE
- F CUMULATIVE RECOVERABLE HELIUM

A	B	C	D	E	F
117221.8	85897.31	55745.98	49415.24	420.8263	1756.985
117221.8	85897.31	55745.98	43084.51	841.6525	3513.97
117221.8	85897.31	55745.98	36753.78	1262.479	5270.954
117221.8	85897.31	55745.98	30423.05	1683.305	7027.939
117221.8	85897.31	55745.98	24092.31	2104.131	8784.924
117221.8	85897.31	55745.98	17761.58	2524.958	10541.91
117221.8	85897.31	55745.98	11430.85	2945.784	12298.89
117221.8	85897.31	55745.98	5100.116	3366.61	14055.88
117221.8	85897.31	55745.98	-1230.617	3787.436	15812.86
117221.8	85897.31	55745.98	-7561.35	4208.263	17569.85

```
  OF SYMBOLS

PRESSURE EQUIV. TO 850FT. S.W.                          PSIA 377.774
                TO 850FT. S.W. MINUS 0.5FT.             PSIA  377.5518
PTC FLASK WP P2 =  3000
COMPRESSIBILITY FOR P  AT  35 DEGREES F, Z =   1.012836
                    P  AT  88 DEGREES F, Z1 =  1.011496
                    P  AT 110 DEGREES F, Z2 =  1.010965
                    P1 AT  35 DEGREES F, Z3 =  1.012829
                    P1 AT  88 DEGREES F, Z4 =  1.011489
                    P1 AT 110 DEGREES F, Z5 =  1.010958
                    P2 AT  35 DEGREES F, Z6 =  1.101937
                    P2 AT  88 DEGREES F, Z7 =  1.091293
                    P2 AT 110 DEGREES F, Z8 =  1.087075
                3814.7 AT  88 DEGREES F, Z9 =  1.116085
HELIUM DENSITY AT      P  AND  35F, LB/FT3 w  =  0.2809201
                       P1 AND  35F, LB/FT3 w1 =  0.2807569
                       P2 AND  35F, LB/FT3 w2 =   2.050475
                       P  AND  88F, LB/FT3 w3 =  0.254087
                       P1 AND  88F, LB/FT3 w4 =  0.2539393
                       P2 AND  88F, LB/FT3 w5 =   1.870228
                       P  AND 110F, LB/FT3 w6 =  0.2444085
                       P1 AND 110F, LB/FT3 w7 =  0.2442663
                       P2 AND 110F, LB/FT3 w8 = 1.80502
                  3814.7 AND  88F, LB/FT3 w9 =   2.325293
RESERVE FOR HYPERBARIC TREATMENT IN DDC, SCF   24573.21
RESERVE FOR OUTER LOCK OPERATION ONCE,   SCF   5774.705
RESERVE FOR PTC MAINTENANCE ONCE,        SCF   6290.743
*******QUANTITY AVAILABLE FOR DIVING MISSION SCF   117221.8
HELIUM FRACTION IN MIXED GAS  0.9550543
HELIUM FOR SHIP'S MIXED GAS BANK PER BANK SCF   7250.829
 HELIUM FOR PTC MIXED GAS FLASKS SCF   4145.847
 HELIUM FOR PTC HELIUM FLASKS SCF   5426.193
*******QUANTITY AVAILABLE FOR DIVING MISSION SCF   85897.31
HELIUM FOR PRESSURIZATION DDC OUTER LOCK SCF   5774.705
HELIUM FOR PRESSURIZATION DDC INNER LOCK SCF   18798.51
HELIUM FOR PTC PRESSURIZATION SCF 5578.12
*******QUANTITY AVAILABLE FOR DAILY OPERATIONS SCF   55745.98
 DAILY OPERATIONS
DDC TRUNK PRESS. TWICE DAILY SCF   786.3428
PTC TRUNK PRESS. TWICE DAILY SCF   638.9036
 MEDICAL LOCK FOUR DAILY SCF   294.8786
 PTC DELTA T EQUALIZATION,TWICE DAILY SCF   424.9565
PTC TRUNK BLOW AT DEPTH TWICE DAILY SCF   869.3851
 DIVERS USE WITH 0.008 IN.ORIFICE MARK II SCF 2858.58
 LOSS IN PTC SCRUBBER CHANGE ONCE EVERY TWO DAYS SCF   36.85982
DAILY LEAKAGE DDC, INNER & OUTER LOCK     SCF   342.9717
DAILY LEAKAGE PTC,                        SCF   77.85457
TOTAL DAILY LEAKAGE DDC AND PTC           SCF   420.8263
HELIUM USE DAILY FOR DIVING OPS         SCF   5909.906
HELIUM RECOVERABLE DURING DIVING OPS  SCF/DAY   1756.985
```

APPENDIX D

PROGRAM - HELIUM TRANSFER TIME CALCULATION

```
        MTAS          -  EFN    SOURCE STATEMENT   -   IFN(S)  -

C  HELIUM TRANSFER TIME CALCULATION     T. BRINKER  CODE 6432     X68002
C*        CASDAC 242053 MTAS          HANSEN 6154E 62434
      DIMENSION ITYPE(50),   PRESS1(50),   PRESS2(50),   P(2)
      DIMENSION DENSTY(2),    ATIME(50),   PTANK(50),   WTRANS(50)
      DIMENSION PHOLD1(2), PHOLD2(2)
      EQUIVALENCE (PHOLD1(2),PRESS1(1)), (PHOLD2(2),PRESS2(1))
   10 FORMAT(8F10.2)
   11 FORMAT( 4F10.2)
  111 FORMAT(/1X25HTOTAL TIME OF TRANSFER = , F9.2,2X,7HMINUTES)
  130 FORMAT(1X,5HOPER.,6X,15HBOTTLE PRESSURE,5X,4HMASS,6X,4HTANK,4X,9HO
     /PERATION,4X,4HTIME)
  140 FORMAT(1X,5HCOUNT,7X,4HFROM,5X,2HTO,5X,19HTRANSFERED PRESSURE/)
  200 FORMAT(///30X,10HINPUT DATA//)
  201 FORMAT(10X,31HVOLUME OF ON BOARD STORAGE BANK,11X,1H=,F8.1,2X,7HCU
     1 FEET/10X,31HDESIGN PRESSURE OF STORAGE BANK,11X,1H=,F8.1,2X,4HPSI
     2G/10X32HMINIMUM PRESSURE OF STORAGE BANK/  12X,31HBEFORE PUMPING M
     3AY BE INITIATED,9X,1H=,F8.1,2X,4HPSIG)
  204 FORMAT(10X,35HVOLUME OF SUPPLY BANK (100 BOTTLES),7X,1H=,F8.1,2X,7
     1HCU FEET/10X,43HINITIAL DELIVERY PRESSURE OF SUPPLY BANK =,F8.1,2X
     2,4HPSIG/10X,43HMINIMUM (RETURN) PRESSURE OF SUPPLY BANK =,F8.1,2X,
     34HPSIG/10X,21HPUMP CLEARANCE VOLUME,21X,1H=,F8.1,2X,7HPERCENT)
  205 FORMAT(10X,29HDURATION OF ONE PUMPING CYCLE,13X,1H=,F8.1,2X,9HMINU
     1TE(S))
  202 FORMAT(10X,38HVOLUME DISPLACED BY PUMP IN ONE MINUTE,4X,1H=,F8.1,
     12X,7HCU FEET/10X,27HPOLYTROPIC PROCESS EXPONENT,15X,1H=,F8.1/10X,
     237HTEMPERATURE OF GAS (ASSUMED CONSTANT),5X,1H=,F8.1,2X,5HDEG-F/
     310X,23HHELIUM GAS CONSTANT (R),19X,1H=,F8.1,2X,12HFT-LBF/LBM-R//)
  203 FORMAT(30X,13HGENERAL NOTES/ 17X,36HPRESSURES EXPRESSED IN PSI(ABS
     1OLUTE)/17X,39HMASS TRANSFERS EXPRESSED IN MASS POUNDS/17X,33HTIME
     2PERIODS EXPRESSED IN MINUTES//)
  777 READ(5,10)  VSTOR,VSUPLY,T,PBOTIN,PBOTFI,PSTORF,PSTORM,R                 1
      READ(5,11)  CLEAR,POLY,DISPL,TIME                                        2
      WRITE(6,200)                                                             3
      WRITE(6,201) VSTOR,PSTORF,PSTORM                                         4
      WRITE(6,204) VSUPLY,PBOTIN,PBOTFI,CLEAR                                  5
      WRITE(6,205)  TIME                                                       6
      WRITE(6,202) DISPL,POLY,T,R                                              7
      WRITE(6,203)                                                             8
      WRITE(6,130)                                                             9
      WRITE(6,140)                                                            10
      TOTVOL=VSTOR+VSUPLY
      CLEAR=CLEAR/100.
      TIMSUM=0.0
      TR=T+460.
      PFINAL=PSTORF+14.7
      PTEST=PBOTIN+14.7
      ICOUNT=1
      Z=1. +3.25*10.**(-5)*(PSTORM+14.7)                                      12
      WTMIN=((PSTORM+14.7)*144.*VSTOR)/(Z*R*TR)
      ATIME(ICOUNT)=0.0
      ITYPE(ICOUNT)=0
      Z=1.+3.25*10.**(-5)*P(1)                                                16
      DENSTY(1)=(P(1)*144.)/(Z*R*TR)
      WBOTLE=DENSTY(1)*VSUPLY
      WRESDU=DENSTY(2)*VSUPLY
      WTEQU=WBOTLE-WRESDU
   50 WT2=WT2+WTEQU
      IF(WTMIN-WT2) 30,30,40
   40 PRESS1(ICOUNT)=P(1)
      PRESS2(ICOUNT)=P(2)
      PTANK(ICOUNT)=(WT2*R*TR)/(144.*VSTOR-3.25*10.**(-5)*WT2*R*TR)           22
      WTRANS(ICOUNT)=WTEQU
      ICOUNT=ICOUNT+1
      GO TO 50
C  INITIALIZATION FOR OPERATIONS.
   30 PRESS1(ICOUNT)=P(1)
      ICOUNT=ICOUNT-1
      WT2=WT2-WTEQU
      ICHECK=0
      IPRINT=0
      LOGIC=0
      ILAST=0
      WTSUM=WT2+WBOTLE
C  EQUALIZING OPERATION.
   90 ICOUNT=ICOUNT+1
      ATIME(ICOUNT)=0.0
      ITYPE(ICOUNT)=0
      P(1)=(WTSUM*R*TR)/(144.*TOTVOL-3.25*10.**(-5)*WTSUM*R*TR)               37
      PRESS2(ICOUNT)=P(1)
      PTANK(ICOUNT)=P(1)
      ZA=1.+3.25*10.**(-5)*P(1)                                               40
      WT1=(P(1)*144.*VSUPLY)/(ZA*R*TR)
      WTRANS(ICOUNT)=WBOTLE-WT1
      WT2=WT2+WTRANS(ICOUNT)
      P(2)=P(1)
```

PROGRAM (Continued)

```
C  PUMPING OPERATION.
   70 ICOUNT=ICOUNT+1
      IF(ICOUNT-51) 300,301,302
  301 CALL OUTPUT(ICOUNT,ILAST,ITYPE,PRESS1,PRESS2,WTRANS,PTANK,ATIME,TI
     1MSUM,PHOLD1,PHOLD2)
      ICOUNT=1                                                            47
      GO TO 71
  300 CONTINUE
      IF(IPRINT) 302,71,304
  304 CALL OUTPUT(ICOUNT,ILAST,ITYPE,PRESS1,PRESS2,WTRANS,PTANK,ATIME,TI
     1MSUM,PHOLD1,PHOLD2)
      GO TO 305                                                           53
   71 CONTINUE
      PRESS1(ICOUNT)=P(1)
      A=.67+CLEAR-CLEAR*(P(2)/P(1))**(1./POLY)
      B=(DISPL*TIME*P(1)*144.)/(ZA*R*TR)                                  57
      WTRANS(ICOUNT)=A*B
      WT1=WT1-WTRANS(ICOUNT)
      PTEMP=(WT1*R*TR)/(144.*VSUPLY-WT1*R*TR*(3.25*10.**(-5)))
      IF(PTEMP-PBOTFI-14.7) 20,60,60                                      60
   60 P(1)=PTEMP
      ATIME(ICOUNT)=TIME
      ITYPE(ICOUNT)=1
   61 WT2=WT2+WTRANS(ICOUNT)
      P(2)=(WT2*R*TR)/(144.*VSTOR -WT2*R*TR*(3.25*10.**(-5)))
      IF(P(2)-PFINAL) 99,100,100                                          67
  100 IPRINT=1
   99 CONTINUE
      IF(P(2)-PTEST) 80,81,81
   81 ICHECK=-1
   80 IF(LOGIC) 73,72,9999
   73 PTANK(ICOUNT)=P(2)
      LOGIC=0
      GO TO 62
   72 CONTINUE
      IF(ICHECK) 63,64,9999
   64 PRESS1(ICOUNT)=PRESS2(ICOUNT-1)
   63 PRESS2(ICOUNT)=P(1)
      PTANK(ICOUNT)=P(2)
      GO TO 70
   20 LOGIC=-1
      PRESS2(ICOUNT)=PBOTFI+14.7
      P(1)=PBOTIN+14.7
      PDIFF=PRESS1(ICOUNT-1)-PRESS2(ICOUNT-1)
      PDELTA=PRESS1(ICOUNT)-PRESS2(ICOUNT)
      ATIME(ICOUNT)=(PDELTA/PDIFF)*TIME
      ITYPE(ICOUNT)=1
      Z=1.+3.25*10.**(-5)*PRESS1(ICOUNT)
      WTRANS(ICOUNT)=(PRESS1(ICOUNT)*VSUPLY*144.)/(R*TR*Z)-WRESOU          96
      GO TO 61
   62 WTSUM=WT2+WBOTLE
      PRESS1(ICOUNT+1)=P(1)
      IF(ICHECK) 86,90,9999
   86 ZA=1.+3.25*10.**(-5)*P(1)
      WT1=(P(1)*144.*VSUPLY)/(ZA*R*TR)                                    105
      GO TO 70
  305 WRITE(6,111) TIMSUM
      GO TO 9999                                                          107
  302 WRITE(6,303)
  303 FORMAT(/25HPROGRAM ERROR TERMINATION/)                              109
 9999 GO TO 777
      END
```

```
         OUTPUT     -  EFN    SOURCE STATEMENT   -  IFN(S)  -           04/23/68

      SUBROUTINE OUTPUT(ICOUNT,ILAST,ITYPE,PRESS1,PRESS2,WTRANS,PTANK,AT
     1IME,TIMSUM,PHOLD1,PHOLD2)
  121 FORMAT(I5,5X,2F8.2,2X,F8.3,2X,F10.3,2X,10HEQUALIZING,2X,F5.2)
  122 FORMAT(I5,5X,2F8.2,2X,F8.3,2X,F10.3,2X,7HPUMPING,5X,F5.2)
      DIMENSION ITYPE(50), PRESS1(50),PRESS2(50), WTRANS(50),PTANK(50)
      DIMENSION ATIME(50),PHOLD1(2),PHOLD2(2)
      ICOUNT=ICOUNT-1
      DO 120 I=1,ICOUNT
      KCOUNT=ILAST+I
      IF(ITYPE(I)) 2,2,3
    2 WRITE(6,121)KCOUNT,PRESS1(I),PRESS2(I),WTRANS(I),PTANK(I),ATIME(I)     9
      GO TO 119
    3 WRITE(6,122)KCOUNT,PRESS1(I),PRESS2(I),WTRANS(I),PTANK(I),ATIME(I)     16
  119 TIMSUM=TIMSUM+ATIME(I)
  120 CONTINUE
      ILAST=ILAST+ICOUNT
      PHOLD1(1)=PRESS1(ICOUNT)
      PHOLD2(1)=PRESS2(ICOUNT)
      RETURN
      END
```

IBLDR

UNUSED CORE 76654 THRU 77014

INPUT DATA

VOLUME OF ON BOARD STORAGE BANK	=	24.0	CU FEET
DESIGN PRESSURE OF STORAGE BANK	=	3000.0	PSIG
MINIMUM PRESSURE OF STORAGE BANK BEFORE PUMPING MAY BE INITIATED	=	200.0	PSIG
VOLUME OF SUPPLY BANK (100 BOTTLES)	=	60.0	CU FEET
INITIAL DELIVERY PRESSURE OF SUPPLY BANK	=,	3000.0	PSIG
MINIMUM (RETURN) PRESSURE OF SUPPLY BANK	=,	200.0	PSIG
PUMP CLEARANCE VOLUME	=	5.0	PERCENT
DURATION OF ONE PUMPING CYCLE	=	9.0	MINUTE(S)
VOLUME DISPLACED BY PUMP IN ONE MINUTE	=	0.6	CU FEET
POLYTROPIC PROCESS EXPONENT	=	1.6	
TEMPERATURE OF GAS (ASSUMED CONSTANT)	=	70.0	DEG-F
HELIUM GAS CONSTANT (R)	=	386.3	FT-LBF/LBM-R

GENERAL NOTES
PRESSURES EXPRESSED IN PSI(ABSOLUTE)
MASS TRANSFERS EXPRESSED IN MASS POUNDS
TIME PERIODS EXPRESSED IN MINUTES

OPER. COUNT	BOTTLE PRESSURE FROM	TO	MASS TRANSFERED	TANK PRESSURE	OPERATION	TIME
1	3014.70	2094.72	33.105	2094.718	EQUALIZING	0.
2	2094.72	1970.17	4.625	2410.262	PUMPING	9.00
3	1970.17	1855.06	4.306	2709.567	PUMPING	9.00
4	1855.06	1748.48	4.014	2993.465	PUMPING	9.00
5	1748.48	1649.66	3.745	3262.734	PUMPING	9.00

TOTAL TIME OF TRANSFER = 36.00 MINUTES

INPUT DATA

VOLUME OF ON BOARD STORAGE BANK	=	24.0	CU FEET
DESIGN PRESSURE OF STORAGE BANK	=	3000.0	PSIG
MINIMUM PRESSURE OF STORAGE BANK BEFORE PUMPING MAY BE INITIATED	=	200.0	PSIG
VOLUME OF SUPPLY BANK (100 BOTTLES)	=	50.0	CU FEET
INITIAL DELIVERY PRESSURE OF SUPPLY BANK	=,	3000.0	PSIG
MINIMUM (RETURN) PRESSURE OF SUPPLY BANK	=,	200.0	PSIG
PUMP CLEARANCE VOLUME	=	5.0	PERCENT
DURATION OF ONE PUMPING CYCLE	=	9.0	MINUTE(S)
VOLUME DISPLACED BY PUMP IN ONE MINUTE	=	0.6	CU FEET
POLYTROPIC PROCESS EXPONENT	=	1.6	
TEMPERATURE OF GAS (ASSUMED CONSTANT)	=	70.0	DEG-F
HELIUM GAS CONSTANT (R)	=	386.3	FT-LBF/LBM-R

GENERAL NOTES
PRESSURES EXPRESSED IN PSI(ABSOLUTE)
MASS TRANSFERS EXPRESSED IN MASS POUNDS
TIME PERIODS EXPRESSED IN MINUTES

OPER. COUNT	BOTTLE PRESSURE FROM	TO	MASS TRANSFERED	TANK PRESSURE	OPERATION	TIME
1	3014.70	1974.23	31.316	1974.225	EQUALIZING	0.
2	1974.23	1833.96	4.375	2270.364	PUMPING	9.00
3	1833.96	1706.10	4.021	2547.296	PUMPING	9.00
4	1706.10	1589.31	3.700	2806.296	PUMPING	9.00
5	1589.31	1482.43	3.410	3048.545	PUMPING	9.00

TOTAL TIME OF TRANSFER = 36.00 MINUTES

INPUT DATA

VOLUME OF ON BOARD STORAGE BANK	=	24.0	CU FEET
DESIGN PRESSURE OF STORAGE BANK	=	3000.0	PSIG
MINIMUM PRESSURE OF STORAGE BANK BEFORE PUMPING MAY BE INITIATED	=	200.0	PSIG
VOLUME OF SUPPLY BANK (100 BOTTLES)	=	80.0	CU FEET
INITIAL DELIVERY PRESSURE OF SUPPLY BANK	=,	3000.0	PSIG
MINIMUM (RETURN) PRESSURE OF SUPPLY BANK	=,	200.0	PSIG
PUMP CLEARANCE VOLUME	=	5.0	PERCENT
DURATION OF ONE PUMPING CYCLE	=	9.0	MINUTE(S)
VOLUME DISPLACED BY PUMP IN ONE MINUTE	=	0.6	CU FEET
POLYTROPIC PROCESS EXPONENT	=	1.6	
TEMPERATURE OF GAS (ASSUMED CONSTANT)	=	70.0	DEG-F
HELIUM GAS CONSTANT (R)	=	386.3	FT-LBF/LBM-R

GENERAL NOTES
PRESSURES EXPRESSED IN PSI(ABSOLUTE)
MASS TRANSFERS EXPRESSED IN MASS POUNDS
TIME PERIODS EXPRESSED IN MINUTES

OPER. COUNT	BOTTLE PRESSURE FROM	TO	MASS TRANSFERED	TANK PRESSURE	OPERATION	TIME
1	3014.70	2267.73	35.652	2267.726	EQUALIZING	0.
2	2267.73	2166.00	4.980	2611.402	PUMPING	9.00
3	2166.00	2070.31	4.713	2943.275	PUMPING	9.00
4	2070.31	1980.20	4.463	3263.713	PUMPING	9.00

TOTAL TIME OF TRANSFER = 27.00 MINUTES