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A COMPUTER SIMULATION

OF A

HYPERBARIC CHAMBER ENVIRONMENT

A MAJOR REPORT

BY

SCOTT ROBERT LISTER

Submitted to Dr. Robert E. Randall at
Texas A & M University
in partial fulfillment of the requirements for the degree of
MASTER OF ENGINEERING

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ABSTRACT

A hyperbaric chamber environment is simulated using a FORTRAN computer program. This program allows the user to input data files of varying chamber conditions and provides a detailed output which can be used for design or chamber operations. Specifically, this program determines life support, temperature and humidity control, and power requirements. After developing the theory and describing the program in detail, complete examples simulating a hyperbaric chamber at 2000 fsw, a submarine lockout chamber at 400 fsw, and a shallow underwater habitat at 50 fsw are demonstrated.

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CHAPTER I

INTRODUCTION

A hyperbaric environment exists in a facility which may be pressurized from one to several hundred atmospheres. Edmonds (1976) defines a hyperbaric chamber as an environmental pressure vessel where the ambient pressure can be increased from one atmosphere to many times atmospheric pressure depending on the structural capabilities of the vessel concerned. Hyperbaric chambers are also known as recompression chambers and decompression chambers. A recompression chamber is used for compressing a patient or diver as part of a therapeutic regime or for training. A decompression chamber is used to decompress a subject already exposed to increased pressure. Miller and Koblick (1984) define an underwater habitat as a facility which acts as a survival shelter allowing humans to survive and live on the ocean floor continuously for several weeks. Hyperbaric chambers, underwater habitats, diving bells, and submarine lock-out chambers require unique design considerations to account for the additional pressures and the effect on human physiology and thermodynamic properties.

History

Hyperbaric chambers have had medical uses for over 300 years. Edmonds (1976), Miller and Koblick (1984), Shilling et al. (1976), and U. S. Navy Diving Gas Manual (1991) provide a chronological history of hyperbaric chambers:

1662 - The first use of a hyperbaric chamber in medicine was made by a British physician, Dr. Henshaw. This chamber was pressurized and depressurized by a pair of organ bellows.

1830's - Three Frenchmen, Junod (1834), Tabarie (1838), and Pravaz (1837) renewed interest in hyperbaric chambers. Junod's chamber was a 1.6 m diameter sphere capable of pressures up to 4 atm. He noted the euphoric effect of compressed air. Tabarie claimed improvement in the treatment of lung disease. Pravaz built a large chamber capable of holding 12 patients at a time.

1850's - A rapid rise in the construction of hyperbaric chambers was observed. Compressed air was provided by steam engines and chambers capable of simultaneously treating up to 50 patients were built.

1860 - The first hyperbaric chamber in North America was built in Ashawa, Canada.

1891 - The first chamber in the United States was built in Rochester, NY.

1921 - Orval J. Cunningham of Kansas City, MO constructed the world's largest hyperbaric chamber. It was 5 stories high, had a diameter of 20 meters, and was equipped with amenities suitable to a first class hotel.

Since 1920's - Numerous hyperbaric chambers have been designed for treatment of divers. With the progress of hyperbaric and diving medicine, chambers are becoming increasingly complex.

1960's - The French and Americans began work on underwater

habitats. The French built Conshelf I & II while the United States built Man-in-the-Sea I & II and Sealab.

Modern Hyperbaric Facilities include:

1) Ocean Simulation Facility (OSF) - located at the U. S. Navy Experimental Diving Unit in Panama City, FL. This chamber is one of the world's largest man-rated hyperbaric facilities with a depth capability of 2250 fsw. A wide range of experiments in biomedical studies, human factors verification, and deep diving systems performance tests are conducted in wet and dry chambers.

2) Naval Medical Research Institute (NMRI) - located in Bethesda, MD. This complex is the U. S. Navy's largest hyperbaric complex fully devoted to research and contains three dry chambers and a vertical wetpot rated to 2280 fsw and two dry chambers rated to 3370 fsw. NMRI conducts hyperbaric research focused on the biomedical and physiological problems encountered by the fleet diver.

3) Duke University's Hyperbaric Chamber - located in Durham, NC. This facility is capable of employing any desired gas at high pressures ranging from 150,000 ft of altitude to 1000 fsw. Research is conducted on acoustic speech modification, high pressure nervous syndrome and carbon dioxide effects.

A typical experimental hyperbaric facility is shown in figure 1.1.

Several factors must be considered when designing a hyperbaric chamber. NAVFAC DM-39 (1982) addresses the

following design requirements:

- 1) Pressure vessel design including material selection, wall thickness, welding requirements, connections, view ports, and doors.
- 2) Fire protection and extinguishing systems.
- 3) Electrical, utility, and communication systems.
- 4) Life support systems including mixed gas breathing systems, carbon dioxide control, and oxygen replenishment.
- 5) Temperature and humidity control.
- 6) Power requirements.

The objective of this program is to determine life support, temperature and humidity control, and power requirements.

During most hyperbaric chamber designs, these factors are analyzed separately and compiled into a finished design. This program allows the user to input varying design considerations and provides a detailed output of design requirements. The most unique capability of this program is the use of a computer to determine the thermodynamic and psychrometric properties. Traditionally, psychrometric charts have been used to determine dehumidification, moisture removal, and ultimately energy requirements. Although specially developed psychrometric charts are available for the higher pressures required in a hyperbaric environment, they are time consuming and lack the accuracy of a computer program. Additionally, reading values off these charts requires non-linear interpolation. Therefore, the necessary relationships were developed to replace the psychrometric chart and simulate a

hyperbaric chamber environment.

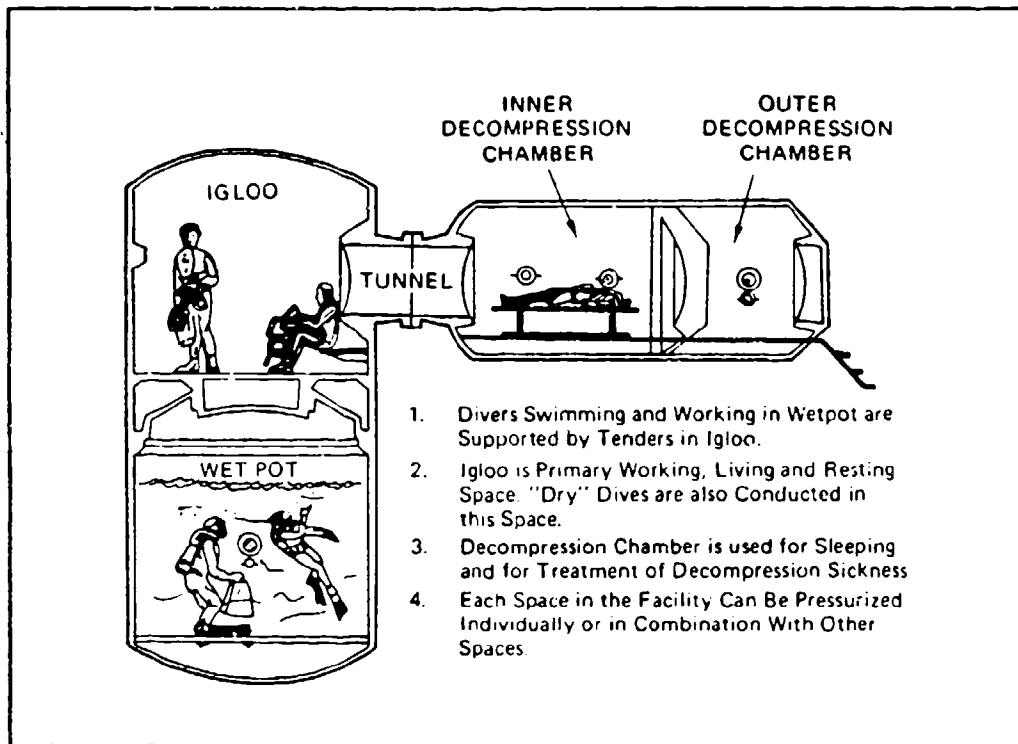


Figure 1.1 Typical Experimental Hyperbaric Facility
(Shilling et al. 1976)

Objectives

Based upon relevant aspects of human physiology, this program determines the ideal diving-gas mixture along with an acceptable range of diving-gas mixtures for a given depth or pressure. Additionally, the required ventilation rate without carbon dioxide absorbers or the amount of absorption material (sodasorb) for saturation diving is calculated. Various properties of the selected diving-gas mixture are determined, and by using thermodynamic properties of the gas, the heating and cooling requirements are calculated. Finally, the energy

requirements for dehumidification and reheating to a desired temperature are determined along with moisture removal requirements.

CHAPTER II

THEORY FOR DESIGN OF HYPERBARIC ENVIRONMENTS

Basic Physiology

A basic knowledge of human physiology is required to determine an acceptable diving-gas mixture for varying depths or pressures. While a given mixture may be acceptable at one pressure, it can cause discomfort or even be fatal at other pressures. The percentage of oxygen required to sustain life decreases as pressure increases in order to maintain an acceptable oxygen partial pressure.

The respiratory system of the body is responsible for oxygen uptake and carbon dioxide removal. Oxygen uptake is governed by two main factors listed by U. S. Navy Diving Gas Manual (1971):

1. Respiratory Minute Volume
2. Effectiveness in which the lung extracts oxygen from alveolar gas.

Respiratory minute volume, which is defined as the product of the respiratory rate (breaths/min) and the tidal volume (volume/breath), determines the duration of exposure of blood to alveolar air. The effectiveness in which the lung extracts oxygen from alveolar gas depends upon 1) composition and volume of air supplied and 2) partial pressures.

The transfer of gases takes place due to differences in partial pressures. The transfer of oxygen occurs with no complications if the oxygen partial pressure is between 0.16

and 1.6 atm for short periods of time. However, if the oxygen partial pressure is below 0.16 atm, anoxia (oxygen shortage) which may lead to fainting and possible brain damage can occur. Likewise, if the oxygen partial pressure exceeds 1.6 atm, oxygen poisoning which may lead to convulsions and unconsciousness may occur. NOAA Diving Manual (1991) states that a 1.6 atm oxygen partial pressure can only be tolerated for up to 45 minutes and that the maximum oxygen partial pressure for long periods should not exceed 0.5 atm. NOAA Diving Manual (1991) also recommends that for long term exposures in a hyperbaric chamber or underwater habitat the oxygen partial pressure of the diving-gas should be between 0.3 and 0.4 atm. Figure 2.1 shows the percentage of oxygen in the diving-gas mixture as a function of depth and oxygen partial pressure. Additionally, Figure 2.1 shows acceptable mixture ranges for a given depth and acceptable depth ranges for a given mixture.

Under atmospheric conditions, the partial pressure of oxygen is 0.21 atm since the percentage of oxygen in air is approximately 21%. Therefore, at the surface, divers may safely breathe 100% oxygen for short periods (hours) since the oxygen partial pressure is only 1.0 atm, well below the 1.6 atm upper limit. However, as depth increases, the pressure also increases and 1.6 atm can be quickly exceeded using air as the diving-gas. Equations 2.1 and 2.2 show the relationship between pressure (psia) and feet of sea water (fsw).

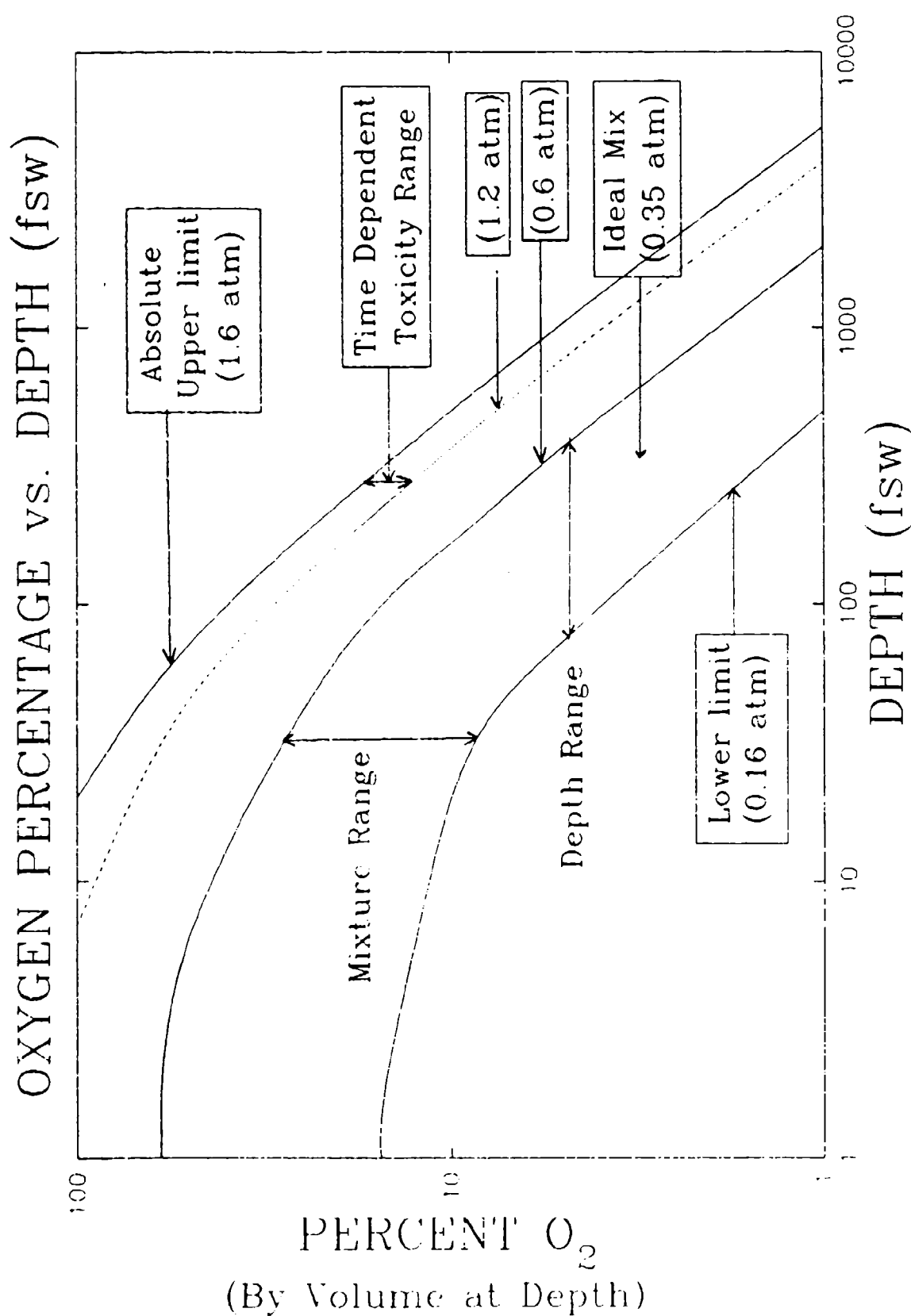


Figure 2.1 Percentage of O_2 in diving-gas mixture as a function of depth and oxygen partial pressure.
(NOAA Diving Manual 1991)

$$P(\text{psia}) = \left(\frac{d(\text{fsw}) + 33.066}{33.066} \right) (14.696) \quad 2.1$$

$$d(\text{fsw}) = 2.25P - 33.066 \quad 2.2$$

where,

$$33.066 \text{ fsw} = 1 \text{ atm}$$

$$1 \text{ atm} = 14.696 \text{ psia}$$

Additionally, the partial pressure of oxygen for given conditions can be determined from equations 2.3 and 2.4.

$$PPO_2 = \left(\frac{d(\text{fsw})}{33.066} + 1.0 \right) (\%O_2) \quad 2.3$$

$$PPO_2 = \left(\frac{P(\text{psia})}{14.696} \right) (\%O_2) \quad 2.4$$

From equation 2.3 it can be shown that the greatest depth in which air can be safely used as a diving-gas without exceeding 1.6 atm partial pressure is 218 fsw.

In addition to quickly exceeding the allowable amount of oxygen, the presence of nitrogen renders air an undesirable breathing gas at depth. Under atmospheric conditions the partial pressure of nitrogen is low and no effects are felt. However, when the partial pressure of nitrogen is sufficiently high, nitrogen narcosis or rapture of the deep occurs. Nitrogen narcosis presents symptoms similar to alcohol

intoxication and can be extremely dangerous while diving at great depths. Table 2-1 indicates the events which may occur while diving with high pressure nitrogen at depth (Randall 1992). Therefore, air is not a suitable diving-gas and is not generally used for depths below 150 fsw. The advantage of using air when possible is that it is inexpensive, and a chamber can be ventilated continuously without the use of carbon dioxide absorbers which are addressed later.

Table 2-1 Effects of Nitrogen Narcosis (Randall 1992)

100 - 150 fsw	light head, some euphoria
150 - 200 fsw	jovial, some dizziness
200 - 250 fsw	laughter may approach hysteria simple tasks cannot be performed without mistakes
300 fsw	depression
350 fsw	may approach unconsciousness

Since helium is an inert gas which eliminates the narcosis effect, it is often used at depths greater than 150 to 200 fsw. However, helium does have the side effects which are listed in the NOAA Diving Manual (1991). One of these side effects is speech distortion which increases with depth. Speech distortion can be overcome by using helium speech scramblers. A second problem with helium is that its use results in rapid body heat loss since the thermal conductivity

of helium is six times that of air. To counter this problem, the diving-gas must be heated for dives below 800 fsw. A third problem associated with helium is the high pressure nervous syndrome (HPNS) which causes tremors in the hands and jerky movements of the limbs. This problem can be reduced by using a slow rate of compression. Alternatives to helium are also listed in the NOAA Diving Manual (1991). These alternatives include neon and hydrogen. Neon has the advantages over helium of a lower thermal conductivity and less speech distortion. However, neon is much more expensive and creates more breathing resistance. Hydrogen is easier to breathe at depth, but it causes more speech distortion than helium, has a higher thermal conductivity, and can be explosive. Other alternatives may be under development, but are beyond the scope of this report.

This program recommends diving-gas mixtures based upon a helium-oxygen mixture. Smaller percentages of oxygen can be mixed with helium to provide a diving-gas mixture which can sustain life without the risk of oxygen poisoning at deeper depths.

Gas Mixtures

The ideal diving-gas mixture is determined from an oxygen partial pressure of 0.35 atm. Equation 2.5 calculates the percent oxygen in the ideal diving-gas mixture.

$$\%O_{2_{ideal}} = \left(\frac{0.35}{P_{atm}} \right) \times 100\%$$

2.5

Since the diving-gases only contain helium and oxygen, equation 2.6 calculates the percent helium in the ideal diving-gas mixture.

$$\%He_{ideal} = 100 - \%O_2$$

2.6

The minimum and maximum allowable limits for oxygen percentage are calculated by equations 2.7 and 2.8 based upon oxygen partial pressures of 0.16 and 0.6 atm respectively as previously discussed.

$$\%O_{2_{min}} = \left(\frac{0.16}{P_{atm}} \right) \times 100\%$$

2.7

$$\%O_{2_{max}} = \left(\frac{0.6}{P_{atm}} \right) \times 100\%$$

2.8

If the maximum allowable oxygen percentage is greater than 21%, air is recommended as the diving-gas mixture. However, in most cases a hyperbaric chamber operates in an environment which necessitates the use of a helium-oxygen mixture.

For a given diving-gas mixture, the pressure (psia) and

depth (fsw) ranges are calculated using equations 2.9 - 2.12.

$$P_{\min} = \left(\frac{16.0}{\%O_2} \right) (14.696) \quad 2.9$$

$$P_{\max} = \left(\frac{60.0}{\%O_2} \right) (14.696) \quad 2.10$$

$$d_{\min} = \left(\frac{16.0}{\%O_2} \right) (33.066) - 33.066 \quad 2.11$$

$$d_{\max} = \left(\frac{60.0}{\%O_2} \right) (33.066) - 33.066 \quad 2.12$$

These ranges are also shown in the previous Figure 2.1.

Chamber Ventilation

Ventilation is required to remove carbon dioxide and replenish oxygen to sustain life. When air is used, the required ventilation rate must be sufficient to flush the chamber to an acceptable level of carbon dioxide. This rate shall be referred to as the "free ventilation rate". The free ventilation rate is more than sufficient to provide enough oxygen to sustain life. Since air is relatively inexpensive, the free ventilation rate is desirable when utilizing air and carbon dioxide scrubbers are not required to keep the environment carbon dioxide free.

The free ventilation rate must be sufficient to maintain an environment at or below acceptable partial pressure levels of carbon dioxide. As with oxygen, the partial pressure of carbon dioxide increases with depth. For extended periods of time, the maximum allowable partial pressure of carbon dioxide should not exceed 0.005 atm. Figure 2.2 shows the maximum allowable CO₂ partial pressure with respect to mission duration. It is evident that as the mission duration increases, the smaller the carbon dioxide partial pressure must be in order to be tolerated. In the event that CO₂ partial pressure exceeds the allowable, hypercapnia or carbon dioxide excess can occur. Table 2-2 lists the four zones of hypercapnia.

Table 2-2 Effects of Hypercapnia

Zone I	- No effect at low CO ₂ partial pressures
Zone II	- Minor perceptive changes
Zone III	- Distracting discomfort
Zone IV	- Dizziness, stupor, unconsciousness

Carbon dioxide production is determined by equation 2.13,

$$CO_{2p} = (R_q) (O_{2c}) (N_d) \quad 2.13$$

EFFECTS OF CARBON DIOXIDE

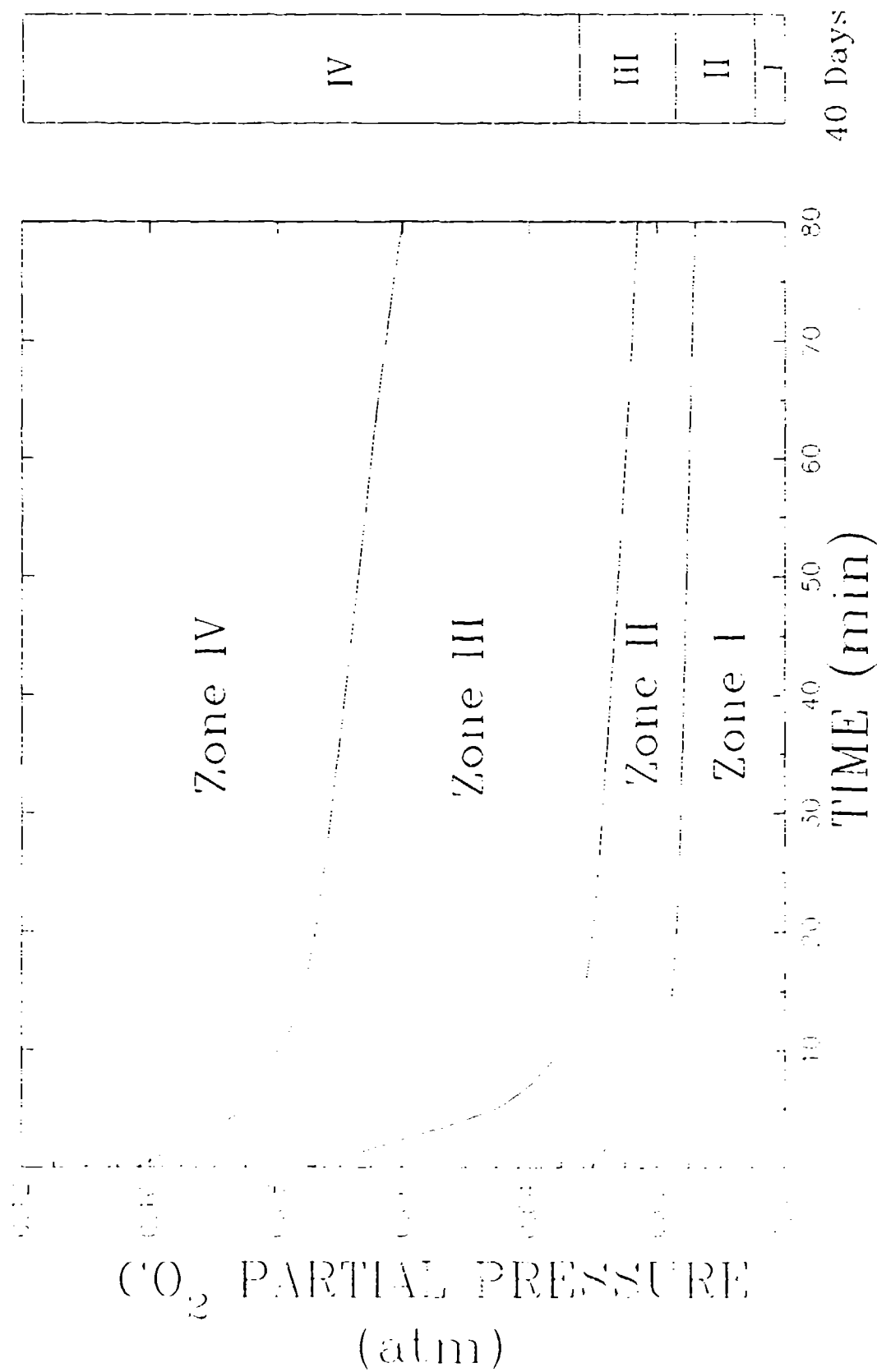


Figure 2.2 Relation of Physiological effects to CO₂
Partial Pressure and Exposure Period
(U. S. Navy Diving Gas Manual 1971)

where,

CO_{2p} = carbon dioxide production (SCFM)

R_q = respiratory quotient (0.9)

O_{2c} = oxygen consumption (SCFM)

N_d = number of divers

Oxygen consumption is determined by the working conditions listed in Table 2-3.

Table 2-3 Oxygen Consumption of Working Conditions

<u>Condition</u>	<u>Description</u>	<u>O₂ consumption</u>
1	Resting	0.5 SLM / 0.0177 SCFM
2	Light Work	0.7 SLM / 0.0247 SCFM
3	Moderate Work	1.5 SLM / 0.0530 SCFM
4	Heavy Work	2.0 SLM / 0.0707 SCFM
5	Severe Work	3.0 SLM / 0.1060 SCFM

Figure 2.3 shows the oxygen consumption in Standard Liters per Minute (SLM) for each of the working conditions. Standard conditions exist at 14.696 psia and 70° F.

In order to determine the free ventilation rate, a steady state condition and complete mixing are assumed. The volumetric flow rate of air at depth (V_{air}) in ft³/min is determined by equation 2.14.

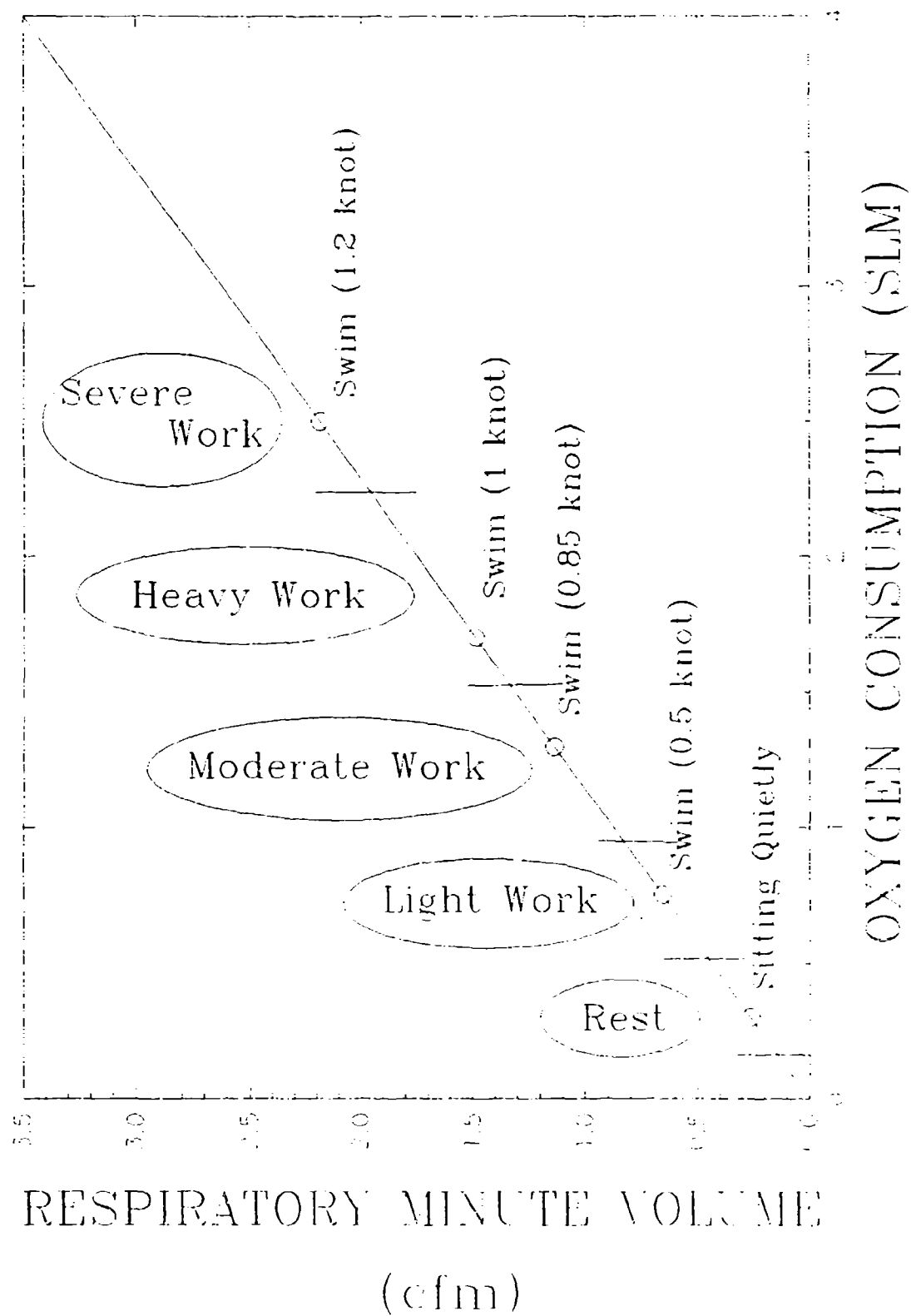


Figure 2.3 Relation of Respiratory Volume and Oxygen Consumption Type and Level of Exertion (Randall 1992)

2.14

$$V_{air} = \frac{mRT}{PCO_2}$$

where,

m = the mass flow rate of CO₂ (lb_{CO2}/minute)

R = the gas constant for CO₂ (35.11 lb/lbmole-R)

T = the initial temperature (R)

PCO₂ = the partial pressure of CO₂ (psf)

(0.005 atm or 10.58 psf is recommended for times
greater than 8 hours)

The ventilation rate (S_{air}) in Standard Cubic Feet per Minute
(SCFM) is calculated by equation 2.15.

2.15

$$S_{air} = \left(\frac{(V_{air}) (P_{psia})}{14.696} \right)$$

The mass flow rate of CO₂ is calculated by equation 2.16.

2.16

$$m = \frac{(14.696 \text{ psia}) (144 \text{ psia/psf}) (CO_{2p})}{(35.11 \text{ ft-lb/lbmole-R}) (530 \text{ R})}$$

where, 14.696 psia and 530 R are standard conditions.

Equation 2.16 can be simplified to equation 2.17.

2.17

$$m = (0.1137) (CO_{2p})$$

where m is expressed in $\text{lb}_{\text{CO}_2}/\text{minute}$.

Since a steady-state condition is assumed, it is important to determine how long it takes to reach this condition at the beginning of a mission or when conditions change. The time required to reach a 95% steady-state condition can be derived from equation 2.18.

$$PCO_2 = \left(\frac{mRT}{V_{air}} \right) \left[1 - e^{-\left(\frac{V_{air}}{V_{ch}} \right) (t)} \right] \quad 2.18$$

where V_{ch} = the interior volume of the chamber (ft^3)

Rearranging to solve for t yields equation 2.19.

$$t = \left(\frac{V_{ch}}{V_{air}} \right) \ln \left[1 - \left(\frac{V_{air} PCO_2}{mRT} \right) \right] \quad 2.19$$

By substituting in the values for PCO_2 (0.005 atm), R (35.11 ft-lb/lbmole-R), and a 95% steady-state condition, equation 2.19 becomes equation 2.20.

$$t = \left(\frac{V_{ch}}{V_{air}} \right) \ln \left[1 - \left(\frac{(.95)(.005)(14.7)(144)(V_{air})}{(35.11)(mT)} \right) \right] \quad 2.20$$

Carrying out the multiplication yields equation 2.21.

$$t = \left(\frac{(-0.0167)(V_{ch})}{V_{air}} \right) \left(\ln \left[1 - \left(\frac{(0.2863)(V_{air})}{mT} \right) \right] \right) \quad 2.21$$

where the factor 0.0167 converts t from minutes to hours.

Carbon Dioxide Removal

In most cases, the working depth or pressure requires a helium-oxygen mixture for reasons previously stated. In these cases scrubbers are used to remove carbon dioxide from the chamber. Therefore, pure oxygen is injected but care must be taken to ensure proper mixing with helium in the chamber. This mixing occurs while the gas mixture is recirculating through the dehumidification and scrubbing system.

The amount of pure oxygen required to sustain the divers (O_{2r}) in Standard Cubic Feet per Minute (SCFM) is determined from equation 2.22.

$$O_{2r} = (O_{2c})(N_d) \quad 2.22$$

where oxygen consumption (O_{2c}) was previously determined from the diver working conditions. The amount of CO_2 produced (lb_{CO_2}) in pounds per minute is calculated by equation 2.23.

$$lb_{CO_2} = (m)(t_d)(60) \quad 2.23$$

where t_d is the mission duration and the factor of 60 converts minutes to hours.

NAVFAC DM-39 (1982) lists three chemicals used as carbon dioxide absorbents. These chemicals and their properties are shown on Table 2-4. Baralyme is no longer used in hyperbaric chambers and Lithium Hydroxide is too expensive and difficult to handle for routine use. Therefore, Sodasorb is the chemical absorbent used in this program. The amount of Sodasorb (LB_s) required for each mission is calculated from equation 2.24 assuming a 50% efficiency.

$$LB_s = \frac{lb_{CO_2}}{0.245} \quad 2.24$$

Although it is possible to obtain higher absorbent efficiencies, canister design, temperature, humidity, and moisture condensation must be considered. The 50% efficiency is a conservative estimate used for design purposes. During actual chamber operations, chemical detection tubes must be used to accurately determine when to change carbon dioxide absorbent canisters. The number of carbon dioxide absorbent canisters required for a mission will depend on the capabilities of individual hyperbaric chambers.

Diving-Gas Mixture Properties

Properties of the diving-gas mixture must be accurately determined in order to calculate energy and dehumidification

Table 2-4 Characteristics of Carbon Dioxide Absorbents
(NAVFAC DM-39 1982)

Characteristic	Absorbent		
	Baralyme	Lithium hydroxide	Sodasorb
Density (lb/ft ³)	65.4	28.0	55.4
Theoretical CO ₂ absorption (lb CO ₂ /lb)	0.39	0.92	0.49
Useful CO ₂ absorption (based on 50% efficiency) (lb CO ₂ /lb)	0.195	0.46	0.245

requirements which will be discussed later. Properties of concern include molecular weight, specific heat, and density of the selected diving-gas mixture.

The molecular weight of a substance is defined as the weight in pounds of one pound-mole of the substance. The molecular weight of the diving-gas mixtures is dependent upon the percentages of oxygen and helium in the mixture and therefore, decreases as the percent oxygen in the mixture decreases. This in turn decreases the density which minimizes the energy requirements. If the diving-gas is air, the molecular weight is 29.0 lb/lb-mole. Otherwise, the mole fractions of oxygen and helium in the diving-gas mixture must first be determined. Mole fractions (X) are determined by equations 2.25 and 2.26. The sum of the mole fractions must always equal 1.

$$X_{O_2} = \frac{\%O_2}{100}$$

2.25

$$X_{He} = 1 - X_{O_2}$$

2.26

Once mole fractions are determined, the molecular weight in lb/lb-mole can be calculated from equation 2.27.

$$MW = [(X_{O_2}) (MW_{O_2})] + [(X_{He}) (MW_{He})]$$

2.27

where,

$$MW_{O_2} = 32.00 \text{ lb/lb-mole}$$

$$MW_{He} = 4.0026 \text{ lb/lb-mole}$$

The specific heat at constant pressure (C_p), in units of BTU/lb-mole, of the diving-gas mixture must be known for determining energy requirements. C_p is defined by equation 2.28.

$$C_p = \left(\frac{\partial h}{\partial T} \right)_p$$

2.28

where, h is the enthalpy and T is temperature.

Given the mole fractions previously determined, C_p in BTU/lb-mole can be calculated from equation 2.29.

$$C_p = [(X_{O_2}) (C_{p_{O_2}})] + [(X_{He}) (C_{p_{He}})]$$

2.29

where,

$$C_{pO_2} = 6.95 \text{ BTU/lb-mole}$$

$$C_{pHe} = 4.965 \text{ BTU/lb-mole}$$

When air is used as the diving-gas, C_p is 6.95 BTU/lb-mole.

Table 2-5 lists the molecular weights and specific heats of common helium/oxygen mixtures and air.

Table 2-5 Properties of Common Diving-Gas Mixtures

Diving-Gas Mixture (%O ₂ /%He)	C_p (BTU/lb-mole)	MW (lb/lb-mole)
1/99	4.985	4.283
5/95	5.064	5.403
10/90	5.164	6.802
15/85	5.263	8.202
20/80	5.362	9.602
40/60	5.759	15.202
Air	6.950	29.000

Density of air is calculated using the ideal gas equation of state since air will only be used down to 150 fsw (81.36 psia). The ideal equation of state is shown as equation 2.30.

$$PV = nR_u T$$

2.30

where,

P = absolute pressure (psf)

V = volume (cu ft)

n = number of moles

R_u = Universal Gas Constant (1544.0 ft-lb/lbmole-R)

T = absolute temperature (R)

Equation 2.30 can be simplified and rearranged to solve for density in equation 2.31.

$$\rho = \frac{(MW)(P)}{R_u T} \quad 2.31$$

Density of helium-oxygen mixtures is determined from the virial equation of state. Dymond and Smith (1980) present the virial equation of state shown as equation 2.32.

$$\frac{PV_m}{R_u T} = 1 + \frac{B(T)}{V_m} + \frac{C(T)}{V_m^2} + \frac{D(T)}{V_m^3} + \dots \quad 2.32$$

where, the values of P, R_u , and T are the same as those used above, and

V_m = molar volume (cu ft/lb-mole)

1 = the first virial coefficient

B(T) = the second virial coefficient

C(T) = the third virial coefficient

D(T) = the fourth virial coefficient

It is common practice to calculate the density of gases based upon only the first three virial coefficients since data beyond this range are scarce. Dymond and Smith (1980) state that uncertainties in the second virial coefficient are relatively small (usually less than 1%) but are much larger for the third virial coefficient. Additionally, the third virial coefficient is much more temperature dependent.

Dymond and Smith (1980) developed the most recent table for determining the second and third virial coefficients for gas mixtures. Equation 2.33 calculates the second virial coefficient of a gas mixture.

$$B_m(T) = B_{11}(T) (X_1)^2 + B_{12}(T) (X_1) (X_2) + B_{22}(T) (X_2)^2 \quad 2.33$$

where,

$B_m(T)$ = the second virial coefficient of the mixture

X_1 = the mole fraction of the first pure gas

X_2 = the mole fraction of the second pure gas

B_{11} = the second virial coefficient of the first pure gas

B_{22} = the second virial coefficient of the second pure gas

B_{12} = the mixed virial coefficient

Equation 2.34 calculates the third virial coefficient of a gas mixture.

$$C_m(T) = C_{111}(T) (X_1)^3 + 3C_{112}(T) (X_1)^2 (X_2) + 3C_{122}(T) (X_1) (X_2)^2 + C_{222}(T) (X_2)^3 \quad 2.34$$

where,

$C_m(T)$ = the third virial coefficient of the mixture

C_{111} = the third virial coefficient of the first pure gas

C_{112} = the contribution of two molecules of the first pure gas and one molecule of the second pure gas

C_{122} = the contribution of one molecule of the first pure gas and two molecules of the second pure gas

Due to the absence of data for determining the third virial coefficients for helium-oxygen mixtures, the density is calculated based upon the first two virial coefficients only. Tables 2-6 lists the virial coefficients for oxygen, helium, and a helium-oxygen mixture respectively from Dymond and Smith (1980). Since this is the most recent data available, it is obvious that very little data exists to determine the mixed virial coefficient for helium-oxygen mixtures.

By substituting the values from Tables 2-6 into equation 2.33, the second virial coefficient in SI units ($\text{cm}^3/\text{g-mole}$) is calculated from equation 2.35.

$$B = [(11.44) (X_{He})^2] - [(8.8) (X_{He}) (X_{O_2})] - [(16.24) (X_{O_2})^2] \quad 2.35$$

Table 2-6 Virial Coefficients of Helium, Oxygen, and Heliox Mixtures
(Dymond and Smith 1980)

Virial Coefficients						
T(C)	Helium		Oxygen		Mixture	
	B	C	B	C	B	C
-183	10.76	277	-241	-12764	-4.4	-
0	11.87	75.5	-21.89	1230	-	-
25	11.44	72.1	-16.24	1163	-	-
50	11.37	72.3	-11.62	1146	-	-

B = cm³/g-mole C = cm⁶/g-mole²

In order to use this coefficient, it must be converted into the English units of ft³/lb-mole. This conversion is made by equation 2.36.

$$\begin{aligned}
 B &= \left(\frac{1 \text{ ft}^3}{28316.85 \text{ cm}^3} \right) \left(\frac{454 \text{ g}}{1 \text{ lb}} \right) \\
 &= (0.0160) (B_{SI})
 \end{aligned}
 \tag{2.36}$$

Solving the virial equation of state for molar volume (ft³/lb-mole) yields equation 2.37.

$$V_m = \frac{(K + \sqrt{K^2 + 4KB})}{2}
 \tag{2.37}$$

where K is a constant defined as $R_u T/P$.

Finally, density is calculated by equation 2.38.

$$\rho = \frac{MW}{V_m} \quad 2.38$$

where MW was calculated in equation 2.27 and molar volume was calculated in equation 2.37.

The U. S. Navy Diving Gas Manual (1971) lists the densities of standard diving-gas mixtures at varying conditions. The resulting error from these equations is less than 0.2%.

Psychrometric Charts

Psychrometric charts are used to compute heating and cooling requirements along with dehumidification and moisture removal requirements. Standard psychrometric charts can be used for calculating the effects of heating and cooling moist air at atmospheric conditions but cannot be used with diving-gas mixtures at much greater depths. Although these charts are available for pressures up to 600 psia (approx. 1300 fsw) in the U. S. Navy Diving Gas Manual (1971), they are time consuming and lack the accuracy of this computer program. Therefore, it is necessary to develop relationships which can be used in computer simulation. Additionally, reading values off these charts requires non-linear interpolation between 100 psia curves. Figure 2.4 shows the psychrometric chart in the

Moisture Mole Fraction
(moles water vapor/mole dry gas)

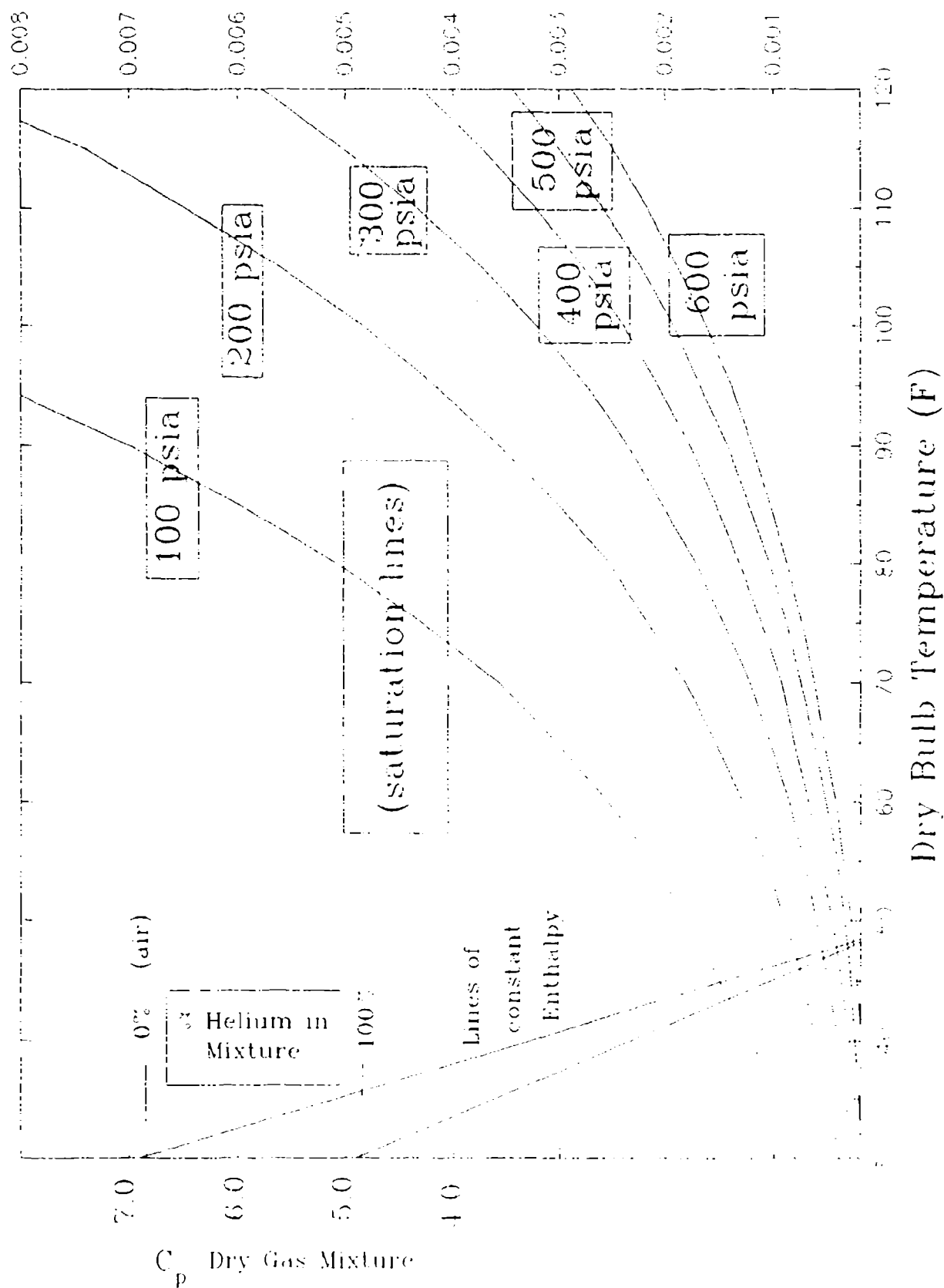


Figure 2.4 Psychrometric Chart for Gas Mixtures at Pressures from 100 to 600 psia (U. S. Navy 1971)

U. S. Navy Diving Gas Manual (1971) developed for gas mixtures at pressures from 100 to 600 psia.

Given the dry bulb temperature and saturation lines at constant pressure, the moisture mole fraction (moles water vapor/moles dry gas) can be determined. The dry bulb temperature is defined by ASHRAE (1967) as the Fahrenheit temperature of moist gas at rest with respect to the temperature-measuring element. The saturation lines at constant pressure represent 100% relative humidity at that pressure.

The moisture mole fraction in moles water vapor/mole dry gas is determined by equation 2.39 if the pressure of the environment and saturation pressure are known.

$$X_{ws} = \frac{P_s}{P - P_s} \quad 2.39$$

where,

X_{ws} = the mole fraction for water vapor at saturation
(moles water vapor/mole dry gas)

P_s = the vapor pressure of water in saturated moist air
(psia)

P = the absolute pressure of the chamber (psia)

The values of P_s have been tabulated by ASHRAE (1967) for various temperatures. These values are reproduced in Table 2-7. Equation 2.40 is a best fit curve through these points

Table 2-7 Vapor Pressure of Water in Saturated Moist Air (psia)
ASHRAE (1967)

Absolute Pressure (Ps)			
Temp (F)	Ps (psia)	Temp (F)	Ps (psia)
40	0.12164	72	0.38856
41	0.12646	73	0.40190
42	0.13145	74	0.41564
43	0.13660	75	0.42979
44	0.14184	76	0.44435
45	0.14746	77	0.45935
46	0.15317	78	0.47478
47	0.15907	79	0.49066
48	0.16517	80	0.50701
49	0.17148	81	0.52382
50	0.17799	82	0.54112
51	0.18473	83	0.55892
52	0.19169	84	0.57722
53	0.19888	85	0.59604
54	0.20630	86	0.61540
55	0.21397	87	0.63530
56	0.22188	88	0.65575
57	0.23006	89	0.67678
58	0.23849	90	0.69838
59	0.24720	91	0.72059
60	0.25618	92	0.74340
61	0.26545	93	0.76684
62	0.27502	94	0.79091
63	0.28488	95	0.81564
64	0.29505	96	0.84103
65	0.30554	97	0.86711
66	0.31636	98	0.89388
67	0.32750	99	0.92137
68	0.33900	100	0.94959
69	0.35084		
70	0.36304		
71	0.37561		

determined from PCMATLAB (1989) with a correlation coefficient of 0.9999565.

$$P_g = (1.9285 \times 10^{-11}) T^5 + (9.8685 \times 10^{-10}) T^4 + (3.3193 \times 10^{-7}) T^3 + (1.9916 \times 10^{-5}) T^2 + (1.0488 \times 10^{-3}) T + (2.2080 \times 10^{-2}) \quad 2.40$$

where T = the chamber temperature ($^{\circ} F$).

The U. S. Navy Diving Gas Manual (1971) states that for total mixture pressures up to 100 psia, no correction for the effect of total pressure on the water-vapor saturation pressure is used. However, above 100 psia, Poynting's equation is used as an estimated correction for total pressure. Glasstone (1947) derives Poynting's Equation shown as equation 2.41.

$$\Delta P_g = \frac{V_1 (\Delta P) (P_g)}{R_u T} \quad 2.41$$

where V_1 is the specific volume of the saturated liquid. Values of V_1 are tabulated by ASHRAE (1967) and are reproduced in Table 2-8 in units of (ft³/lb). To be used in Poynting's Equation, V_1 must be expressed in (ft³/mole). This is easily accomplished by multiplying V_1 by the molecular weight of water (18.0158 lb/lb-mole). Then, the corrected saturation pressure will be calculated from equation 2.42.

Table 2-8 Specific Volume of Saturated Liquid
ASHRAE (1967)

V_l Specific Volume (cu ft/lb)			
Temp (F)	V_l	Temp (F)	V_l
40	0.01602	72	0.01606
41	0.01602	73	0.01606
42	0.01602	74	0.01606
43	0.01602	75	0.01606
44	0.01602	76	0.01606
45	0.01602	77	0.01607
46	0.01602	78	0.01607
47	0.01602	79	0.01607
48	0.01602	80	0.01607
49	0.01602	81	0.01608
50	0.01602	82	0.01608
51	0.01602	83	0.01608
52	0.01602	84	0.01608
53	0.01603	85	0.01609
54	0.01603	86	0.01609
55	0.01603	87	0.01609
56	0.01603	88	0.01610
57	0.01603	89	0.01610
58	0.01603	90	0.01610
59	0.01603	91	0.01610
60	0.01603	92	0.01611
61	0.01604	93	0.01611
62	0.01604	94	0.01611
63	0.01604	95	0.01612
64	0.01604	96	0.01612
65	0.01604	97	0.01612
66	0.01604	98	0.01612
67	0.01615	99	0.01613
68	0.01605	100	0.01613
69	0.01605		
70	0.01605		
71	0.01605		

$$P_g = P_{g_i} + \Delta P_g \quad 2.42$$

where P_{g_i} is the uncorrected saturation pressure. The moisture mole fraction of water vapor at saturation (X_{ws}) is then calculated from equation 2.39.

The molar enthalpy of moisture content at saturation (H) in (BTU/mole dry gas) is calculated from equation 2.43.

$$H = (20,000) X_{ws} \quad 2.43$$

Enthalpy is a thermodynamic property defined by equation 2.44.

$$H = U + PV \quad 2.44$$

where,

U = internal energy

P = absolute pressure

V = volume

Determination of enthalpy is important for calculating energy requirements.

Dehumidification and Energy Requirements

In order to determine dehumidification requirements, the initial and desired relative humidities must be known. Given

the initial and desired relative humidities, the moisture mole fraction and molar enthalpy of moisture content can be determined for both conditions by equations 2.45 - 2.48.

$$X_{w_1} = (RH_1) (X_{ws}) \quad 2.45$$

$$X_{w_2} = (RH_d) (X_{ws}) \quad 2.46$$

$$H_1 = (RH_1) (H) \quad 2.47$$

$$H_2 = (RH_d) (H) \quad 2.48$$

where RH_1 and RH_d are the initial and desired relative humidities expressed in fractions, and X_{ws} and H were previously determined. Once the moisture mole fraction at the desired relative humidity is known, the maximum coil temperature required for dehumidification can be calculated. Equation 2.49 calculates the new saturation pressure (P_g).

$$P_g = \frac{(X_{w_2}) (P)}{1 + X_{w_2}} \quad 2.49$$

Then, the maximum coil temperature (T_c) in ($^{\circ}\text{F}$) can be determined as the intersection of saturation pressure curve at X_{w2} or from equation 2.50.

$$\begin{aligned} T_c = & (2.4135 \times 10^2) P_g^5 - (8.4538 \times 10^2) P_g^4 \\ & + (1.1635 \times 10^3) P_g^3 - (8.1910 \times 10^2) P_g^2 \\ & + (3.5407 \times 10^2) P_g + (7.0106) \end{aligned} \quad 2.50$$

Equation 2.50 was calculated using PCMATLAB (1989) and has a correlation coefficient of 0.999974.

Once the coil temperature is determined, the moist gas mixture enthalpies at the initial and coil temperatures are calculated. Equations 2.51 and 2.52 calculate the moist gas mixture enthalpies in (BTU/lb) at the initial and coil temperatures respectively.

$$H_a = \frac{[(C_p)(T_i) + H_1]}{MW} \quad 2.51$$

$$H_c = \frac{[(C_p)(T_c) + H_2]}{MW} \quad 2.52$$

where the specific heat and molecular weight were previously determined as properties of the diving-gas mixture.

The energy (Q_d) in (BTU/min) required to dehumidify the chamber to the desired relative humidity is calculated from equation 2.53.

$$Q_d = \rho V_{air} (H_a - H_c) \quad 2.53$$

where, V_{air} is either the free ventilation rate for air systems or the recirculation flowrate for helium-oxygen systems. Since the coil temperature is generally colder than the desired diving-gas mixture, the diving-gas must be reheated to a desired temperature. The change in enthalpy from the coil to a desired temperature (T_d) is calculated by equation 2.54.

$$\Delta h = \frac{[(C_p)(T_d - T_c)]}{MW} \quad 2.54$$

Then, the energy required to reheat the diving-gas (Q_r) to the desired temperature is calculated by equation 2.55.

$$Q_r = \rho V_{air} \Delta h \quad 2.55$$

The total energy (Q_t) required by the system for dehumidification and reheat is calculated by equation 2.56.

$$Q_t = Q_d + Q_r \quad 2.56$$

However, energy lost to heat transfer through the chamber

walls depends on insulation and is not considered in this analysis. It would be an additional energy requirement.

Moisture Removal Rate

In all dehumidification processes, moisture removal must be addressed. Due to the rapid cooling of the moist air, water vapor condenses and must be removed from the chamber. In order to determine the moisture removal rate, the humidity ratios at the initial and desired relative humidities must be determined. Equations 2.57 and 2.58 calculate the humidity ratios in pounds water vapor per pounds dry air (lb_w/lb_d) at the initial (W_1) and desired (W_2) relative humidities respectively.

$$W_1 = \frac{(X_{w_1})(18.0158)}{MW} \quad 2.57$$

$$W_2 = \frac{(X_{w_2})(18.0158)}{MW} \quad 2.58$$

where 18.0158 is the molecular weight of water. The moisture removal rate (MRR) in (lb/day) can then be calculated by equation 2.59.

$$MRR = (W_1 - W_2) V_{air} \rho (1440) \quad lb/day \quad 2.59$$

where, V_{air} is either the free ventilation rate or the

recirculation flowrate and the factor of 1440 converts lb/minute to lb/day. This moisture removal rate results from the dehumidification process only. The moisture produced by the carbon dioxide absorbents is not included in this analysis.

CHAPTER III

DESCRIPTION OF SIMULATION

Simulation Structure

This program is designed to simulate hyperbaric chamber environments such as decompression chambers, submarine lockout and pilot chambers, diving bells, underwater habitats, and ocean simulation facilities under different conditions. The theory and equations developed in Chapter II are incorporated into this interactive computer program which is written in Fortran 77 for a 386 personal computer. In order to design a hyperbaric chamber with this program, the input listed in Table 3-1 is required. Given this input, the program calculates values and provides the output listed in Table 3-2.

A flowchart for this program is included as Figure 3.1 and the source code is provided as Appendix B.

Subroutine Description

This program makes use of several subroutines to calculate the required quantities. A description of each subroutine follows in the paragraphs below.

Subroutine "CONVERT" converts depth to pressure. For all subsequent calculations, this program uses absolute pressure. If the user chooses to input a working depth in feet of seawater (fsw), "CONVERT" converts depth to pressure using equation 2.1. This value is returned to the main program and

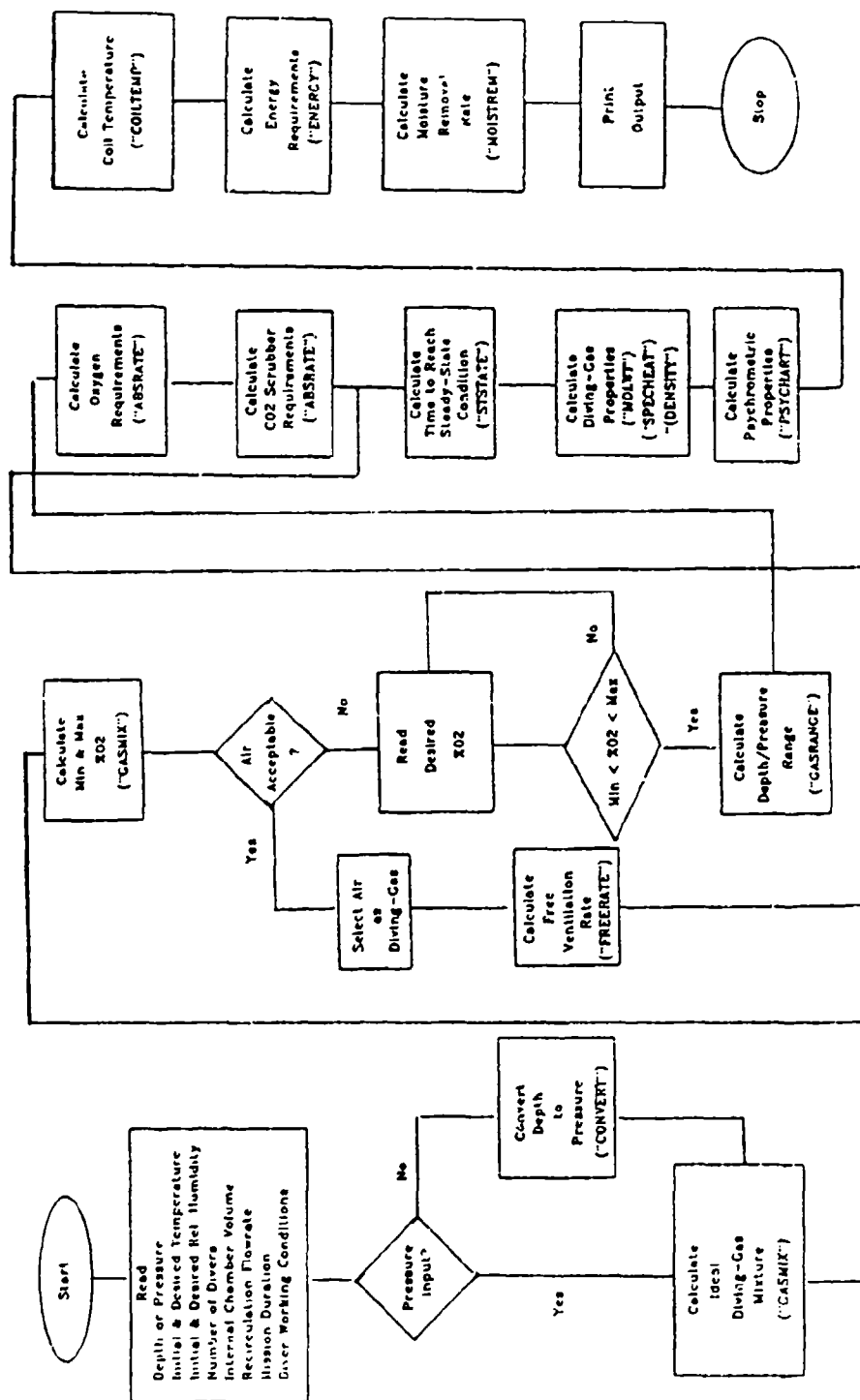


Figure 3.1 Flowchart for "Simulation of a Hyperbaric Chamber Environment"

Table 3-1 Required Program Input

<u>Requirement</u>	<u>Units</u>
1) Working Depth or Pressure	fsw (feet of seawater) psia
2) Initial Temperature	° F
3) Desired Temperature	° F
4) Initial Relative Humidity	%
5) Desired Relative Humidity	%
6) Number of Divers	N/A
7) Internal Volume of Chamber	ft ³
8) Diver Working Conditions	N/A
9)* Mission Duration	hrs
10)* Recirculation Flowrate	ft ³ /min
* - These values are only required if CO ₂ scrubbers are going to be used during the mission.	

used for all future calculations.

Subroutine "GASMIX" calculates the minimum and maximum oxygen percentages for the pressure of interest based upon oxygen partial pressures of 0.16 and 0.6 atm respectively from equations 2.7 and 2.8. If the maximum acceptable oxygen percentage is greater than 21%, the ideal diving-gas mixture is air. All further calculations are then based upon air as the diving-gas mixture. If the maximum acceptable oxygen percentage is less than 21%, the program determines an acceptable oxygen percentage using an IF-THEN statement.

Table 3-2 Program Output

<u>Output</u>	<u>Units</u>
1) Diving-Gas Mixture	%He/%O ₂
2) Oxygen Required or Ventilation Rate	SCFM
3*) Sodasorb Required	lbs
4) Time to Reach 95% Steady-State	hrs
5) Molecular Weight	lb/lb-mole
6) Gas Mixture Density	lb/ft ³
7) Maximum Coil Temperature	° F
8) Dehumidification Energy Requirements	BTU/min
9) Reheat Energy Requirements	BTU/min
10) Moisture Removal Rate	lb/day
* - This value is only provided if CO ₂ scrubbers are used during the mission.	

Subroutine "GASRANGE" calculates a pressure and depth range based upon equations 2.9 - 2.12 after an acceptable diving-gas mixture has been selected. This information is useful if the same diving-gas mixture is used for multiple depths. If the user is planning to operate outside these limits, a different diving-gas mixture should be selected.

Subroutine "FREERATE" determines the ventilation rate required to keep the carbon dioxide partial pressure at an acceptable level when air is used as the diving-gas. First, "FREERATE"

calculates the carbon dioxide production based upon the working conditions and equation 2.13. In order to maintain a CO_2 partial pressure below 0.005 atm, the volumetric flow rates of air at depth and at the surface are calculated from equations 2.14 and 2.15.

Subroutine "ABSRATE" calculates the amount of oxygen required to sustain life, the amount of CO_2 produced, and the amount of Sodasorb required to maintain an acceptable environment when the diving-gas is a helium-oxygen mixture. The amount of oxygen required is calculated by equation 2.22 while the amount of CO_2 produced in pounds is calculated by equation 2.23 and the amount of Sodasorb required is calculated by equation 2.24. The user may wish to design different CO_2 scrubbing systems based upon the amount of CO_2 produced.

Subroutine "STSTATE" calculates the time required to reach a 95% steady-state condition. Since steady-state conditions are assumed, it is important to determine the time required to reach this condition. The time required to reach the 95% steady-state condition is calculated by equation 2.21. This information is useful when beginning a mission or changing conditions.

Subroutines "MOLWT", "SPECHEAT", and "DENSITY" calculate the properties of the selected diving-gas mixture. If the diving-gas mixture is air, the molecular weight and specific heat are

constant values of 29.0 lb/lb-mole and 6.95 BTU/lb-mole respectively.

However, for helium-oxygen mixtures, "MOLWT" calculates the molecular weight from equation 2.27 and "SPECHEAT" calculates the specific heat from equation 2.29. This information is used in subsequent calculations.

"DENSITY" calculates the density of the diving-gas for both air and helium-oxygen mixtures. Since air is only used at low pressures, "DENSITY" determines the density of air from the ideal equation of state, equation 2.31. When helium-oxygen mixtures are used, "DENSITY" calculates density from the virial equation of state, equation 2.32. The second virial coefficient for the mixture is determined from equation 2.35 and converted to English units in equation 2.36. This value is then used to determine the molar volume from equation 2.37, and finally the density is calculated by equation 2.38. This value is used in subsequent energy calculations.

Subroutine "PSYCHART" calculates the moisture mole fraction (X_{ws}) and the enthalpy of moisture content (H) for the diving-gas mixture. First, the vapor pressure of water in saturated moist air (P_g) is calculated from equation 2.40. If the working pressure is less than 100 psia, no correction is required. However, for pressures above 100 psia, P_g is corrected using Poynting's equation 2.41 where the specific volume of the saturated liquid (V_l) is read off of Table 2-8 using an IF-THEN statement. The corrected value of P_g is then

calculated by equation 2.42. The values of X_{ws} and H are calculated from equations 2.39 and 2.43 respectively.

Subroutine "XWSH" calculates the initial and desired moisture mole fractions (X_{w1} and X_{w2}) and molar enthalpies (H_1 and H_2). These properties are determined by the initial and desired relative humidities. The values are calculated based upon X_{ws} and H by equations 2.45 - 2.48.

Subroutine "COILTEMP" calculates the maximum coil temperature required to dehumidify the chamber to the desired relative humidity. The moisture mole fraction at the desired relative humidity (X_{w2}) was calculated by equation 2.46. The new saturation pressure (P_g) is determined by solving equation 2.39 for P_g which leads to equation 2.49. Given P_g , the coil temperature (T_c) is calculated by equation 2.50.

Subroutine "MGMENTH" calculates the moist gas mixture enthalpies entering the cooling coil (H_a) and leaving the cooling coil (H_c) by equations 2.51 and 2.52 respectively. In this program, the temperature entering the cooling coil is assumed to be the initial temperature (T_i) and the temperature leaving the cooling coil is assumed to be the maximum coil temperature (T_c). These values may differ in an actual cooling system.

Subroutine "ENERGY" calculates the energy required for

dehumidification and reheat to the desired temperature. The energy required for dehumidification (Q_d) is calculated by equation 2.53. If the diving-gas is air, the free ventilation rate (V_{air}) calculated by "FREERATE" is used. For helium-oxygen mixtures, the recirculation flowrate input by the user is used as V_{air} . In order to determine the energy required to reheat to a desired temperature (Q_r), the change in enthalpy from the coil temperature to a desired temperature must be calculated by equation 2.54. Then, Q_r is calculated in a similar manner as Q_d by equation 2.55. The total energy required (Q_t) is calculated by equation 2.56.

Subroutine "MOISTREM" calculates the moisture removal rate required for the above dehumidification. First, the humidity ratios at the initial (W_1) and desired (W_2) relative humidities are calculated by equations 2.57 and 2.58. Then, the moisture removal rate is calculated by equation 2.59 where again, V_{air} is the free ventilation rate for air or the recirculation flowrate for helium-oxygen mixtures. The calculations performed by these subroutines are incorporated into the main program, and the results are displayed to the user as program "output". Three examples are discussed in detail in the next chapter.

CHAPTER IV

APPLICATION OF SIMULATION

This program can be used not only to simulate a hyperbaric chamber but also a submarine diver lock-out chamber or an underwater habitat. The following examples demonstrate this program's usefulness for determining the requirements of these cases.

Example 1: Hyperbaric Chamber

This example simulates a hyperbaric chamber used for a deep dive. As a model, the U. S. Navy's Ocean Simulation Facility at the Naval Coastal Systems Center in Panama City, Fl was be used. This facility as shown in Figure 4.1 is capable of pressurization down to 2250 fsw and is described in detail by Shilling et al. (1976) and U. S. Navy Diving Manual (1991). The input conditions for this example are given in Table 4-1. The calculation steps are demonstrated below:

- 1) Since a working depth was input, it was converted to a pressure. By equation 2.1,

$$P = \left(\frac{(2000 + 33.066)}{33.066} \right) (14.696)$$
$$P = 903.6 \text{ psia}$$

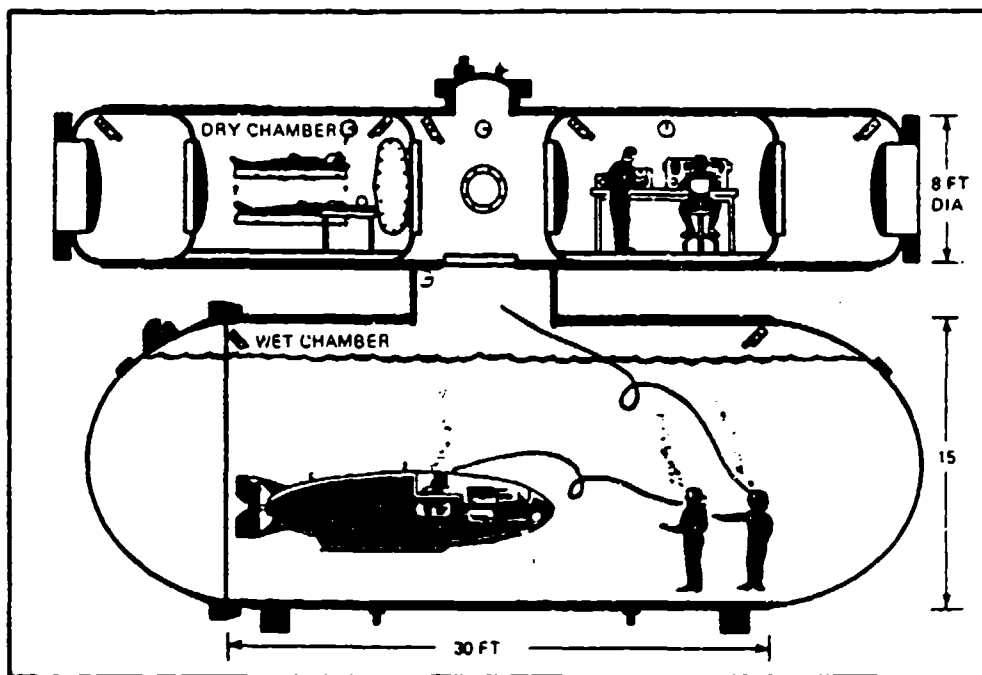


Figure 4.1 Ocean Simulation Facility
(Shilling et al. 1976)

2) The ideal gas mixture for this depth was calculated by equations 2.5 and 2.6.

$$\%O_2 = \left(\frac{0.35}{\frac{903.6}{14.696}} \right) (100\%)$$

$$\%O_2 = 0.57\%$$

$$\%He = 100 - 0.57$$

$$\%He = 99.43\%$$

Table 4-1 Hyperbaric Chamber Simulation Input

Depth (fsw):	2000
Initial/Desired Temperatures (° F):	90/80
Initial/Desired Relative Humidities (%):	90/50
Number of Divers:	6
Internal Chamber Volume (ft ³):	3300
Recirculation Flowrate (cfm):	100
Mission Duration (hrs):	240
Diver Working Conditions:	Light Work

Therefore, the ideal gas mixture was determined to be 0.57% O₂ and 99.43% He.

3) The minimum and maximum oxygen percentages were calculated by equations 2.7 and 2.8.

$$\%O_{2_{min}} = \left(\frac{0.16}{\left(\frac{903.6}{14.696} \right)} \right) (100\%)$$

$$\%O_{2_{min}} = 0.26\%$$

$$\%O_{2_{max}} = \left(\frac{0.6}{\left(\frac{903.6}{14.696} \right)} \right) (100\%)$$

$$\%O_{2_{max}} = 0.98\%$$

Since only mixtures within these levels are acceptable, air could not be used and a 0.5% O_2 and 99.5% helium gas mixture was selected. Therefore, carbon dioxide scrubbers were used and a computation of free ventilation was not needed.

4) The pressure and depth ranges for the gas mixture were calculated from equations 2.9 - 2.12.

$$P_{\min} = \left(\frac{0.16}{0.5} \right) (14.696)$$

$$P_{\min} = 470.3 \text{ psia}$$

$$P_{\max} = \left(\frac{60.0}{0.5} \right) (14.696)$$

$$P_{\max} = 1763.5 \text{ psia}$$

$$d_{\min} = \left[\left(\frac{16.0}{0.5} \right) (33.066) - 33.066 \right]$$

$$d_{\min} = 1025.0 \text{ fsw}$$

$$d_{\max} = \left[\left(\frac{60.0}{0.5} \right) (33.066) - 33.066 \right]$$

$$d_{\max} = 3934.9 \text{ fsw}$$

5) Since a helium-oxygen mixture was used with carbon dioxide scrubbers, the amount of pure oxygen injected into the chamber was calculated by equation 2.22.

$O_{2c} = 0.7 \text{ SLM or } 0.0247 \text{ SCFM for light work}$

$$O_{2r} = (0.0247) (6)$$

$$O_{2r} = 0.1482 \text{ SCFM}$$

6) The amount of carbon dioxide produced and the scrubber requirements were calculated by equations 2.17 and 2.23 - 2.24.

$$m = (0.1137) (0.9) (0.1482)$$

$$m = 0.01517 \text{ lb}_{\text{CO}_2}/\text{min}$$

$$\text{lb}_{\text{CO}_2} = (0.0157) (240) (60)$$

$$\text{lb}_{\text{CO}_2} = 218.4 \text{ lb}$$

$$\text{lb}_s = \left(\frac{218.4}{0.245} \right)$$

$$\text{lb}_s = 891.4 \text{ lb}$$

7) The time required to reach 95% steady-state was determined from equation 2.21 where V_{air} was determined from 2.14.

$$V_{air} = \frac{[(0.01517)(35.11)(549.67)]}{10.58}$$

$$V_{air} = 27.7 \text{ ft}^3/\text{min}$$

$$t = (-0.0167) \left(\frac{3300}{27.7} \right) \ln \left[1 - \frac{(0.2863)(27.7)}{(0.0152)(549.67)} \right]$$

$$t = 5.96 \text{ hrs}$$

8) Next, the diving-gas properties were determined.
Molecular weight was calculated from equations 2.25-2.27.

$$X_{O_2} = \frac{0.5}{100} = 0.005$$

$$X_{He} = \frac{99.5}{100} = 0.995$$

$$MW = [(0.005)(32.00) + (0.995)(4.0026)]$$

$$MW = 4.143 \text{ lb/lb-mole}$$

Specific heat was calculated from equation 2.29.

$$C_p = [(0.005)(6.95) + (0.995)(4.965)]$$

$$C_p = 4.975 \text{ BTU/lb-mole}$$

Density was calculated from equations 2.35 - 2.38.

$$B = [(11.44)(0.995)^2 - (8.8)(0.995)(0.005) - (16.24)(0.005)^2]$$

$$B = 11.2187 \text{ cm}^3/\text{g-mole}$$

$$B = (0.0160)(11.2817)$$

$$B = 0.1805 \text{ ft}^3/\text{lb-mole}$$

$$K = \frac{(1544)(549.67)}{(903.6)(144)}$$

$$K = 6.5226$$

$$V_m = \frac{6.5226 + \sqrt{6.5226^2 + 4(6.5226)(0.1805)}}{2}$$

$$V_m = 0.6185 \text{ ft}^3/\text{lb-mole}$$

$$\rho = \frac{4.143}{6.6984}$$

$$\rho = 0.6185 \text{ lb/ft}^3$$

9) The psychrometric properties were calculated from equations 2.39 - 2.48. The psychrometric chart created for this case is presented as Figure 4.2.

$$P_g = 0.69838 \text{ psia} \quad (\text{from Table 2-7})$$

$$V_1 = 0.01610 \text{ cu ft/lb} \quad (\text{from Table 2-8})$$

$$V_1 = 0.2880 \text{ cu ft/mole}$$

$$\Delta P_g = \frac{[(0.69838)(0.2880)(903.6)(144)]}{[(1544)(549.67)]}$$

$$\Delta P_g = 0.0308 \text{ psia}$$

$$P_g = 0.69838 + 0.0308$$

$$P_g = 0.7292 \text{ psia}$$

$$X_{wg} = \frac{0.7297}{903.6 - 0.7297}$$

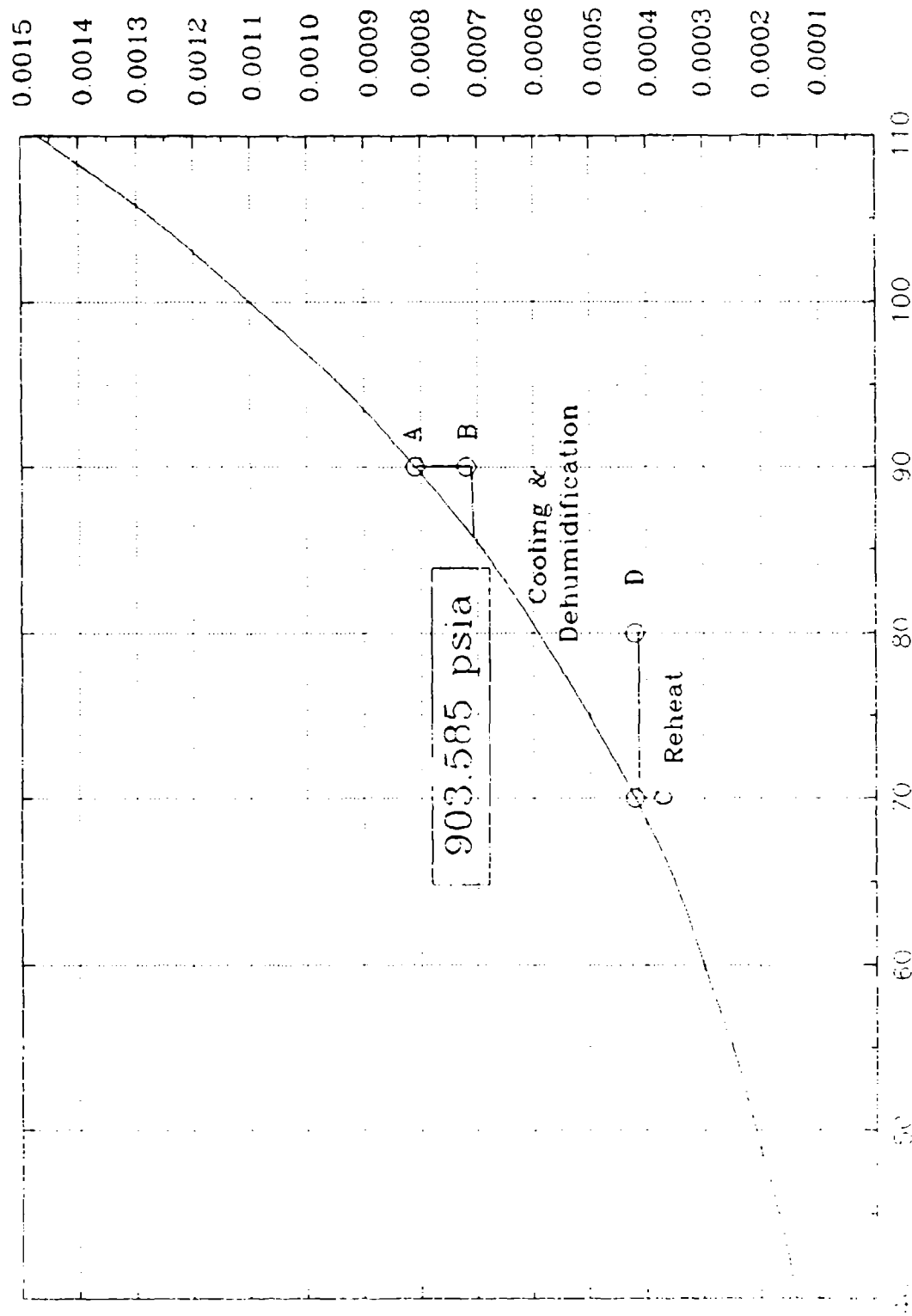
$$X_{wg} = 0.00081 \text{ moles water vapor/mole dry gas}$$

(X_{wg} is shown as point A on Figure 4.2)

$$X_{wl} = (0.9)(0.00081)$$

$$X_{wl} = 0.00072 \text{ moles water vapor/mole dry gas}$$

Moisture Mole Fraction
(moles water vapor/mole dry gas)



Dry Bulb Temperature (F)

Figure 4.2 Psychrometric Chart for 2000 (fsw)

(X_{w1} is shown as point B on Figure 4.2)

$$X_{w2} = (0.5) (0.00081)$$

$$X_{w2} = 0.00041 \text{ moles water vapor/mole dry gas}$$

(X_{w2} is shown as point D on Figure 4.2)

$$H = (20,000) (0.00081)$$

$$H = 16.2 \text{ BTU/mole dry gas}$$

$$H_1 = (0.9) (16.2)$$

$$H_1 = 14.6 \text{ BTU/mole dry gas}$$

$$H_2 = (0.5) (16.2)$$

$$H_2 = 8.1 \text{ BTU/mole dry gas}$$

10) The maximum coil temperature was determined from the psychrometric chart as the intersection of X_{w2} and the 100% saturation curve. This point is at approximately 70° F and is shown as point C on Figure 4.2.

$$T_c = 70^\circ \text{ F}$$

11) The energy requirements were calculated from equations 2.51 - 2.56.

$$H_a = \frac{[4.975)(90) + 14.6]}{4.143}$$

$$H_a = 111.6 \text{ BTU/lb}$$

$$H_c = \frac{[(4.975)(70) + 8.1]}{4.143}$$

$$H_c = 86.0 \text{ BTU/lb}$$

$$Q_d = (0.6185)(100)(111.6 - 86.0)$$

$$Q_d = 1583.4 \text{ BTU/min}$$

$$\Delta h = \frac{[4.975)(80 - 70)]}{4.143}$$

$$\Delta h = 12.0 \text{ BTU/lb}$$

$$Q_r = (0.6185)(100)(12.0)$$

$$Q_r = 742.2 \text{ BTU/min}$$

$$Q_t = 1583.4 + 742.2$$

$$Q_t = 2325.6 \text{ BTU/min}$$

12) The moisture removal rate was calculated from equations 2.57 - 2.59.

$$W_1 = (0.00072) \left(\frac{18.0159}{4.143} \right)$$

$$W_1 = 0.00313 \text{ lb}_w/\text{lb}_d$$

$$W_2 = (0.00041) \left(\frac{18.0158}{4.143} \right)$$

$$W_2 = 0.00178 \text{ lb}_w/\text{lb}_d$$

$$MRR = (0.00313 - 0.00178) (100) (0.6185) (1440)$$

$$MRR = 120.1 \text{ lb/day}$$

The actual program printout is provided as Table 4-2. The slight discrepancies between the example and the actual output were caused by round-off error obtained while working the example.

Table 4-2 Output for Hyperbaric Chamber Simulation

HYPERBARIC CHAMBER SIMULATION	
Input Conditions:	
Pressure (psia):	903.6
Initial/Desired Temperature ($^{\circ}$ F):	90.0/80.0
Initial/Desired Relative Humidity (%):	90.0/50.0
# of Divers/Working Conditions:	6.0/2
Chamber Volume (ft^3):	3300.0
Flow Rate (ft^3/min):	100.0
Mission Duration (hrs):	240.0
Output Conditions:	
Diving-Gas Mixture (%He/%O ₂):	99.5/0.5
Oxygen Required (SCFM):	0.148
CO ₂ Produced (lbs):	218.7
Sodasorb Required (lbs):	892.7
Time to 95% Steady-State (hrs):	6.0
Molecular Weight (lb/lb-mole):	4.143
Gas Mixture Density (lb/ ft^3):	0.6184
Maximum Coil Temperature ($^{\circ}$ F):	70.2
Dehumidification Energy (BTU/min):	1563.5
Reheat Energy (BTU/min):	724.3
Total Energy Requirement (BTU/min):	2287.8
Moisture Removal Rate (lb/day):	125.2

Example 2: Submarine Diver Lock-out Chamber

This example simulates a diver lock-out chamber aboard a submarine used to decompress divers after a mission. The input conditions for this example are given in Table 4-3.

Table 4-3 Diver Lock-out Chamber Simulation Input

Depth (fsw):	400
Initial/Desired Temperatures (° F)	85/78
Initial/Desired Relative Humidities (%):	90/60
Number of Divers:	2
Internal Chamber Volume (ft ³):	100
Recirculation Flowrate (cfm):	10
Mission Duration (hrs):	4
Diver Working Conditions:	Resting

The calculation steps are demonstrated below:

- 1) Since a working depth was input, it was converted to a pressure. By equation 2.1,

$$P = \left(\frac{(400 + 33.066)}{33.066} \right) (14.696)$$
$$P = 192.5 \text{ psia}$$

- 2) The ideal gas mixture for this depth was calculated by equations 2.5 and 2.6.

$$\%O_2 = \left(\frac{0.35}{\left(\frac{192.5}{14.696} \right)} \right) (100\%)$$

$$\%O_2 = 2.67\%$$

$$\%He = 100 - 2.67$$

$$\%He = 97.33\%$$

Therefore, the ideal gas mixture was determined to be 2.67% O₂ and 97.33% He.

3) The minimum and maximum oxygen percentages were calculated by equations 2.7 and 2.8.

$$\%O_{2_{min}} = \left(\frac{0.16}{\left(\frac{192.5}{14.696} \right)} \right) (100\%)$$

$$\%O_{2_{min}} = 1.2\%$$

$$\%O_{2_{max}} = \left(\frac{0.6}{\left(\frac{192.5}{14.696} \right)} \right) (100\%)$$

$$\%O_{2_{max}} = 4.58\%$$

Since only mixtures within these levels air acceptable, air could not be used and a 3% O₂ and 97% He mixture was selected. Therefore, carbon dioxide scrubbers were used

and a computation of free ventilation rate was not needed.

4) The pressure and depth ranges for the gas mixture were calculated from equations 2.9 - 2.12.

$$P_{\min} = \left(\frac{16.0}{3.0} \right) (14.696)$$

$$P_{\min} = 78.4 \text{ psia}$$

$$P_{\max} = \left(\frac{60.0}{3.0} \right) (14.696)$$

$$P_{\max} = 293.9 \text{ psia}$$

$$d_{\min} = \left[\left(\frac{16.0}{3.0} \right) (33.066) - 33.066 \right]$$

$$d_{\min} = 143.3 \text{ fsw}$$

$$d_{\max} = \left[\left(\frac{60.0}{3.0} \right) (33.066) - 33.066 \right]$$

$$d_{\max} = 628.2 \text{ fsw}$$

5) Since a helium-oxygen mixture was used with carbon dioxide scrubbers, the amount of pure oxygen injected into the chamber was calculated by equation 2.22.

$$O_{2c} = 0.5 \text{ SLM or } 0.0177 \text{ SCFM}$$

$$O_{2r} = (0.0177)(2)$$

$$O_{2r} = 0.0354 \text{ SCFM}$$

6) The amount of carbon dioxide produced and the scrubber requirements were calculated by equations 2.17 and 2.23 - 2.24.

$$m = (0.1137)(0.9)(0.0354)$$

$$m = 0.0036 \text{ lb}_{\text{CO}_2}/\text{min}$$

$$\text{lb}_{\text{CO}_2} = (0.0036)(4)(60)$$

$$\text{lb}_{\text{CO}_2} = 0.86 \text{ lb}$$

$$\text{lb}_s = \left(\frac{0.86}{0.245} \right)$$

$$\text{lb}_s = 3.5 \text{ lb}$$

7) The time required to reach 95% steady-state was determined from equation 2.21 where V_{air} was determined from 2.14.

$$V_{\text{air}} = \frac{[(0.0036)(35.11)(544.67)]}{10.58}$$

$$V_{\text{air}} = 6.51 \text{ ft}^3/\text{min}$$

$$t = (-0.0167) \left(\frac{100}{6.51} \right) \ln \left[1 - \frac{(0.2863)(6.51)}{(0.0036)(544.67)} \right]$$

$$t = 0.77 \text{ hrs}$$

8) Next, the diving-gas properties were determined. Molecular weight was calculated from equations 2.25 - 2.27.

$$X_{O_2} = \frac{3.0}{100} = 0.03$$

$$X_{He} = \frac{97.0}{100} = 0.97$$

$$MW = [(0.03)(32.00) + (0.97)(4.0026)]$$

$$MW = 4.843 \text{ lb/lb-mole}$$

Specific heat was calculated from equation 2.29.

$$C_p = [(0.03)(6.95) + (0.97)(4.965)]$$

$$C_p = 5.025 \text{ BTU/lb-mole}$$

Density was calculated from equations 2.35 - 2.38.

$$B = [(11.44)(0.97)^2 - (8.8)(0.97)(0.03) - (16.24)(0.03)^2]$$

$$B = 10.4932 \text{ cm}^3/\text{g-mole}$$

$$B = (0.0160)(10.492)$$

$$B = 0.1679 \text{ ft}^3/\text{lb-mole}$$

$$K = \frac{(1544)(544.67)}{(192.5)(144)}$$

$$K = 30.34$$

$$V_m = \frac{30.34 + \sqrt{30.54^2 + 4(30.54)(0.1679)}}{2}$$

$$V_m = 30.51 \text{ ft}^3/\text{lb-mole}$$

$$\rho = \frac{4.843}{30.51}$$

$$\rho = 0.1587 \text{ lb/ft}^3$$

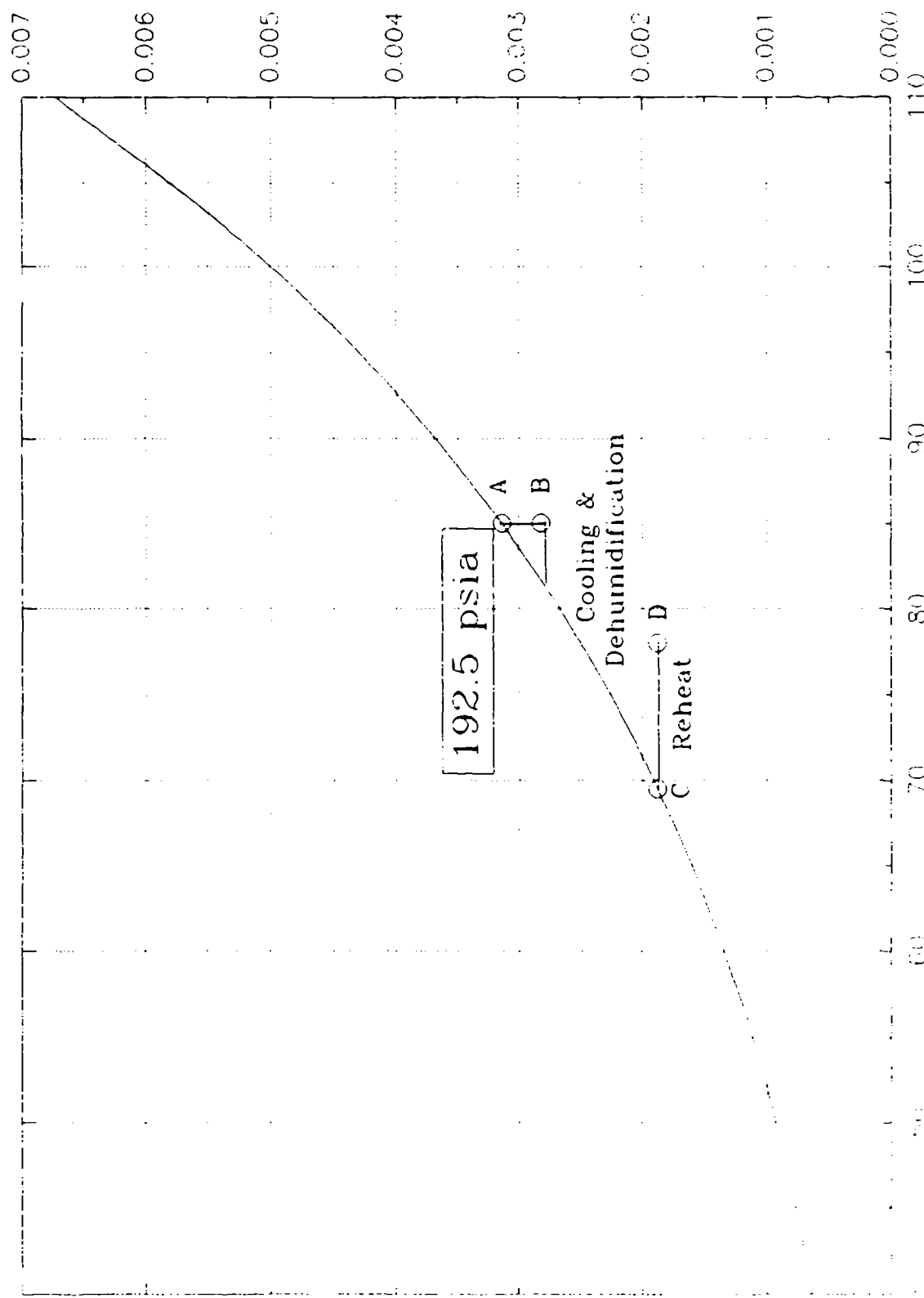
9) The psychrometric properties were calculated from equations 2.39 - 2.48. The psychrometric chart created for this case is presented as Figure 4.3.

$$P_g = 0.59604 \text{ psia (from Table 2-7)}$$

$$V_1 = 0.01609 \text{ cu ft/lb (from Table 2-8)}$$

$$V_1 = 0.2896 \text{ cu ft/mole}$$

Moisture Mole Fraction
(moles water vapor/mole dry gas)



Dry Bulb Temperature (F)

Figure 4.3 Psychrometric Chart for 400 (fsw)

$$\Delta P_g = \frac{[(0.59604)(0.2896)(192.5)(144)]}{[(1544)(544.67)]}$$

$$\Delta P_g = 0.00569 \text{ psia}$$

$$P_g = 0.59604 + 0.00569$$

$$P_g = 0.60173 \text{ psia}$$

$$X_{ws} = \frac{0.60173}{192.5 + 0.60173}$$

$$X_{ws} = 0.00314 \text{ moles water vapor/mole dry gas}$$

(X_{ws} is shown as point A on Figure 4.3)

$$X_{w1} = (0.9)(0.00314)$$

$$X_{w1} = 0.00282 \text{ moles water vapor/mole dry gas}$$

(X_{w1} is shown as point B on Figure 4.3)

$$X_{w2} = (0.6)(0.00314)$$

$$X_{w2} = 0.00188 \text{ moles water vapor/mole dry gas}$$

(X_{w2} is shown as point D on Figure 4.3)

$$H = (20,000) (0.00314)$$

$$H = 62.71 \text{ BTU/mole dry gas}$$

$$H_1 = (0.9) (62.71)$$

$$H_1 = 56.44 \text{ BTU/mole dry gas}$$

$$H_2 = (0.6) (62.71)$$

$$H_2 = 37.63 \text{ BTU/mole dry gas}$$

10) The maximum coil temperature was determined from the psychrometric chart as the intersection of X_{w2} and the 100% saturation curve. This point is at approximately 70° F and is shown as point C on Figure 4.3.

$$T_c = 70^\circ \text{ F}$$

11) The energy requirements were calculated from equations 2.51 - 2.56.

$$H_a = \frac{[(5.025) (85) + 56.44]}{4.843}$$

$$H_a = 99.85 \text{ BTU/lb}$$

$$H_c = \frac{[(5.025)(70) + 37.63]}{4.843}$$

$$H_c = 80.40 \text{ BTU/lb}$$

$$Q_d = (0.1587)(10)(99.85 - 80.40)$$

$$Q_d = 30.9 \text{ BTU/min}$$

$$\Delta h = \frac{[(5.025)(78 - 70)]}{4.843}$$

$$\Delta h = 8.3 \text{ BTU/lb}$$

$$Q_r = (0.1587)(10)(8.3)$$

$$Q_r = 13.2 \text{ BTU/min}$$

$$Q_t = 30.9 + 13.2$$

$$Q_t = 44.1 \text{ BTU/min}$$

12) The moisture removal rate was calculated from equations 2.57 - 2.59.

$$W_1 = (0.00282) \left(\frac{18.0158}{4.843} \right)$$

$$W_1 = 0.01049 \text{ lb}_w/\text{lb}_d$$

$$W_2 = (0.00188) \left(\frac{18.0158}{4.843} \right)$$

$$W_2 = 0.00699 \text{ lb}_w/\text{lb}_d$$

$$MRR = (0.01049 - 0.00699) (10) (0.1587) (1440)$$

$$MRR = 8.0 \text{ lb/day}$$

The actual program printout is provided as Table 4-4. The slight discrepancies between the example and the actual output were caused by round-off error obtained while working the example.

Table 4-4 Output for Diver Lock-out Chamber Simulation

DIVER LOCK-OUT CHAMBER SIMULATION	
Input Conditions:	
Pressure (psia):	192.5
Initial/Desired Temperature ($^{\circ}$ F):	85.0/78.0
Initial/Desired Relative Humidity (%):	90.0/60.0
# of Divers/Working Conditions:	2.0/1
Chamber Volume (ft ³):	100.0
Flow Rate (ft ³ /min):	10.0
Mission Duration (hrs):	4.0
Output Conditions:	
Diving-Gas Moisture (%He/%O ₂):	97.0/3.0
Oxygen Required (SCFM):	0.035
CO ₂ Produced (lbs):	0.9
Sodasorb Required (lbs):	3.5
Time to 95% Steady-State (hrs):	0.8
Molecular Weight (lb/lb-mole):	4.843
Gas Mixture Density (lb/ft ³):	0.1587
Maximum Coil Temperature ($^{\circ}$ F):	70.0
Dehumidification Energy (BTU/min):	30.9
Reheat Energy (BTU/min):	13.2
Total Energy Requirement (BTU/min):	44.1
Moisture Removal Rate (lb/day):	8.0

Example 3: Underwater Habitat

This example simulates a shallow underwater habitat. The French Conshelf II is used as a model. Conshelf II, shown as Figure 4.4, was a shallow water habitat operating in the Red Sea in September of 1963. The breathing gas was air and the mission duration was 1 month. Miller and Koblick (1984) describe this mission in detail. The input conditions for this example are given in Table 4-5. The calculation steps are demonstrated below:

Table 4-5 Underwater Habitat Simulation Input

Depth (fsw):	50
Initial/Desired Temperatures (° F):	95/80
Initial/Desired Relative Humidities (%):	95/50
Number of Divers:	4
Internal Chamber Volume (ft ³):	2000
Diver Working Conditions:	Moderate Work

- 1) Since a working depth was input, it was converted to a pressure. By equation 2.1,

$$P = \left(\frac{(50 + 33.066)}{33.066} \right) (14.696)$$

$$P = 36.9 \text{ psia}$$

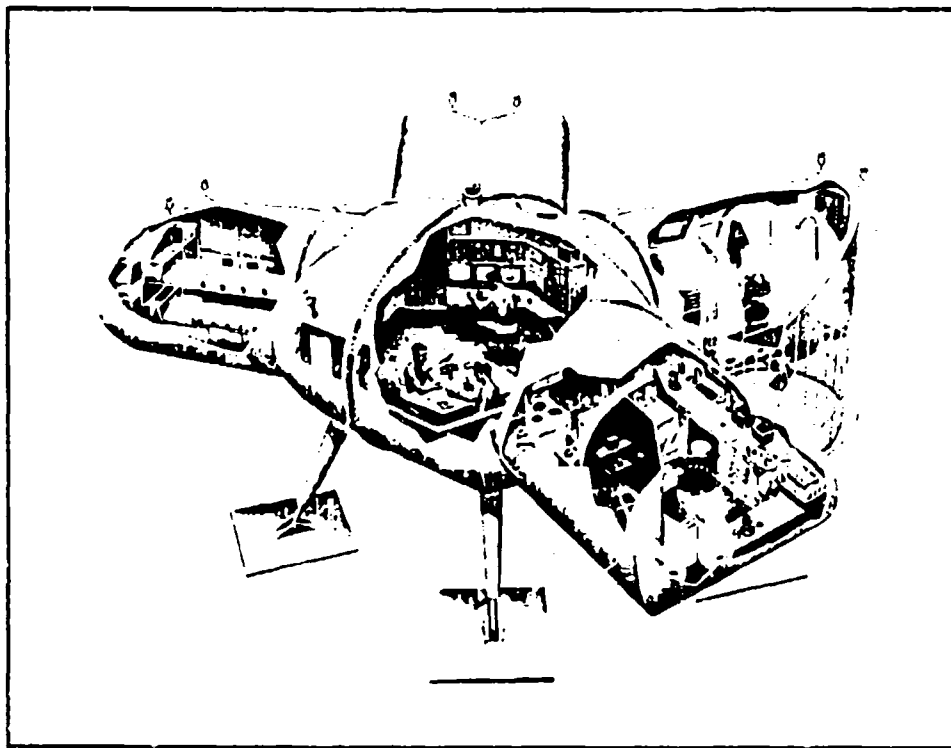


Figure 4.4 Conshelf II Habitat, Starfish House
(Miller and Koblick 1984)

2) The ideal gas mixture for this depth is calculated by equations 2.5 and 2.6.

$$\%O_2 = \left(\frac{0.35}{\left(\frac{36.9}{14.696} \right)} \right) (100\%)$$

$$\%O_2 = 13.9\%$$

$$\%He = 100 - 13.9$$

$$\%He = 86.1\%$$

3) The minimum and maximum oxygen percentages were calculated by equations 2.7 and 2.8.

$$\%O_{2_{\min}} = \left(\frac{0.16}{\left(\frac{36.9}{14.696} \right)} \right) (100\%)$$

$$\%O_{2_{\min}} = 6.37\%$$

$$\%O_{2_{\max}} = \left(\frac{0.60}{\left(\frac{36.9}{14.696} \right)} \right) (100\%)$$

$$\%O_{2_{\max}} = 23.9\%$$

Since any mixture within these levels is acceptable, air (21% O₂) was selected as the diving-gas. Therefore, a free ventilation rate was used to keep the chamber free of carbon dioxide and CO₂ absorbers were not required.

4) The free ventilation rate at depth and from the surface was calculated from equations 2.14 - 2.17.

$$\dot{V}_{O_2} = 1.5 \text{ BLM or } 0.0530 \text{ SCFM for moderate work}$$

$$CO_{2_p} = (0.3) (0.0530) (4)$$

$$CO_{2_p} = 0.1908 \text{ lb/min}$$

$$m = (0.1137)(0.1908)$$

$$m = 0.0217 \text{ lb}_{\text{CO}_2}/\text{min}$$

$$V_{\text{air}} = \frac{[(0.0217)(35.11)(529.67)]}{10.58}$$

$$V_{\text{air}} = 39.9 \text{ ft}^3/\text{min}$$

$$S_{\text{air}} = \frac{[(39.9)(36.9)(529.67)]}{[(14.696)(554.67)]}$$

$$S_{\text{air}} = 95.8 \text{ SCFM}$$

5) The time required to reach a 95% steady-state conditions was determined from equation 2.21.

$$t = (-0.0167) \left(\frac{2000}{39.9} \right) \ln \left[1 - \frac{(0.2863)(39.9)}{(0.0217)(554.67)} \right]$$

$$t = 2.5 \text{ hrs}$$

6) Next, the diving-gas properties were determined. Since the diving-gas was air, the molecular weights and specific heats were 29.0 lb/lb-mole and 6.95 BTU/lb-mole respectively. Density was calculated from the ideal equation of state, equation 2.31.

$$\rho = \frac{[(29.0)(36.9)(144)]}{[(1544)(554.67)]}$$

$$\rho = 0.18002 \text{ lb/ft}^3$$

7) The psychrometric properties were calculated from equations 2.39 - 2.48. The psychrometric chart created for this case is presented as Figure 4.5.

$$P_g = 0.81564 \text{ psia (from Table 2-7)}$$

Since the operating pressure was less than 100 psia, no correction was required for the saturation vapor pressure.

$$X_{ws} = \frac{0.81564}{36.9 - 0.81564}$$

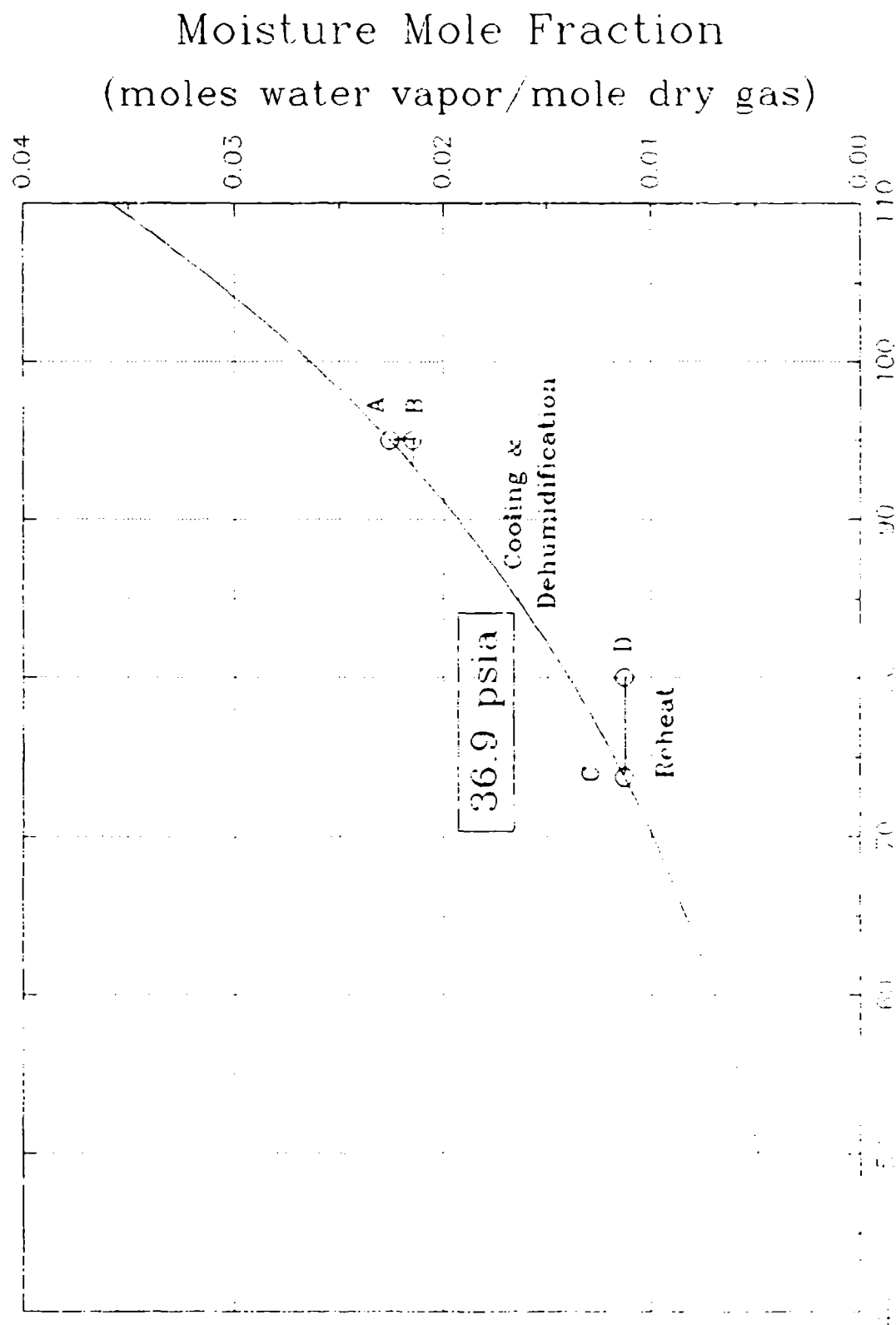
$$X_{ws} = 0.0226 \text{ moles water vapor/mole dry gas}$$

(X_{ws} is shown as point A on Figure 4.5)

$$X_{w1} = (0.95)(0.0226)$$

$$X_{w1} = 0.0215 \text{ moles water vapor/mole dry gas}$$

(X_{w1} is shown as point B on Figure 4.5)



Dry Bulb Temperature (F)

Figure 4.5 Psychrometric Chart for 50 (fsw)

$$X_{w2} = (0.50) (0.0226)$$

$$X_{w2} = 0.0113 \text{ moles water vapor/mole dry gas}$$

(X_{w2} is shown as point D on Figure 4.5)

$$H = (20,000) (0.0226)$$

$$H = 452.0 \text{ BTU/mole dry gas}$$

$$H_1 = (0.95) (452.0)$$

$$H_1 = 429.4 \text{ BTU/mole dry gas}$$

$$H_2 = (0.50) (452.0)$$

$$H_2 = 226.0 \text{ BTU/mole dry gas}$$

8) The maximum coil temperature was determined from the psychrometric chart as the intersection of X_{w2} and the 100% saturation curve. This point is at approximately 73.7° F and is shown as point C on Figure 4.5.

$$T_c = 73.7^\circ \text{ F}$$

9) The energy requirements were calculated from equations 2.51 - 2.56.

$$H_a = \frac{[(6.95)(95) + 429.4]}{29.0}$$

$$H_a = 37.6 \text{ BTU/lb}$$

$$H_c = \frac{[(6.95)(73.7) + 226.0]}{29.0}$$

$$H_c = 25.5 \text{ BTU/lb}$$

$$Q_d = (0.18002)(39.9)(37.6 - 25.5)$$

$$Q_d = 86.9 \text{ BTU/min}$$

$$\Delta h = \frac{[(6.95)(80 - 73.7)]}{29.0}$$

$$\Delta h = 1.51 \text{ BTU/lb}$$

$$Q_r = (0.18002)(39.9)(1.51)$$

$$Q_r = 10.8 \text{ BTU/min}$$

$$Q_t = 86.9 + 10.8$$

$$Q_t = 97.7 \text{ BTU/min}$$

10) The moisture removal rate was calculated from equations 2.57 - 2.59.

$$W_1 = (0.18002) \left(\frac{18.0158}{29.0} \right)$$

$$W_1 = 0.01336 \text{ lb}_w/\text{lb}_d$$

$$W_2 = (0.18002) \left(\frac{18.0158}{29.0} \right)$$

$$W_2 = 0.00702 \text{ lb}_w/\text{lb}_d$$

$$MRR = (0.01336 - 0.00702) (39.9) (0.18002) (1440)$$

$$MRR = 65.5 \text{ lb/day}$$

The actual program printout is provided as Table 4-6. The slight discrepancies between the example and the actual output were caused by round-off error obtained while working the example.

Table 4-6 Output for Underwater Habitat

UNDERWATER HABITAT SIMULATION	
Input Conditions:	
Pressure (psia):	36.9
Initial/Desired Temperature ($^{\circ}$ F):	95.0/80.0
Initial/Desired Relative Humidity (%):	95.0/50.0
# of Divers/Working Conditions:	4.0/3
Chamber Volume (ft^3):	2000.0
Output Conditions:	
Diving-Gas Mixture:	AIR
Free Ventilation Rate at Depth (cfm):	39.9
Free Ventilation Rate (SCFM):	95.8
Time to 95% Steady-State (hrs):	2.5
Molecular Weight (lb/lb-mole):	29.0
Gas Mixture Density (lb/ft^3):	0.18002
Maximum Coil Temperature ($^{\circ}$ F):	73.8
Dehumidification Energy (BTU/min):	87.0
Reheat Energy (BTU/min):	10.8
Total Energy Requirement (BTU/min):	97.8
Moisture Removal Rate (lb/day):	65.4

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A FORTRAN computer program has been developed to simulate a hyperbaric chamber environment. Although hyperbaric chambers have been used for many years, increasing complexity requires innovative design procedures. This program allows the user to design life support systems, temperature and humidity control equipment, and determine energy requirements for hyperbaric chambers, submarine diver lockout chambers, and underwater habitats. By using this program, the design engineer can simulate a variety of scenarios and determine the design criteria for a specific chamber.

Conclusions:

- 1) Acceptable diving-gas mixtures are obtained by ensuring the oxygen partial pressure of the mixture remains between 0.16 and 1.6 atm for short periods of time and below 0.6 atm for extended operations.
- 2) In order to eliminate the narcosis effects of nitrogen on the diver, helium-oxygen mixtures are used below 150 fsw.
- 3) The partial pressure of carbon dioxide (CO_2) must be maintained below 0.005 atm during extended missions in order to eliminate discomfort and possible injury to the divers. This can be accomplished by ventilation of the chamber or by using a CO_2 absorption system. Ventilation is only recommended when air is used as the diving-gas due to the cost

of helium.

4) A CO₂ absorption system consists of canisters filled with sodasorb. The diving-gas mixture flows through these canisters and the CO₂ is removed. Although this program can be used to estimate the duration of the CO₂ canisters if the amount of sodasorb contained is known, a chemical detection system should always be used to determine when to replace the absorbent material.

5) The molecular weight and specific heat at constant pressure of the diving-gas mixture can be determined from the component mole fractions.

6) The density of helium-oxygen mixtures is determined from the virial equation of state. Three virial coefficients are required to accurately calculate density. Although, the first two virial coefficients have been accurately determined for helium and oxygen, only one second virial coefficient for helium-oxygen mixtures has been determined. Additionally, no third virial coefficients for helium-oxygen mixtures have been determined to date. Therefore, extremely accurate density calculations for helium-oxygen mixtures are not obtainable at this time.

7) Psychrometric charts have been used for years to determine dehumidification and cooling requirements. Relationships were developed to compute moisture mole fractions (X_{w_g}) allowing a computer simulation without using the psychrometric charts. This program is easier to use and more accurate than psychrometric charts.

8) Enthalpy of moisture content (H) is easily calculated once X_{ws} is determined. Enthalpy is an important thermodynamic property for calculating energy requirements.

9) Dehumidification and energy requirements can be determined for varying conditions if the initial and desired temperatures and relative humidities are known. However, the total energy requirement neglects heat loss due to heat transfer between the chamber and the environment. Additionally, the coil temperature required to perform the desired dehumidification and the moisture removal rate can be determined.

Recommendations:

1) Pressure vessel design of a hyperbaric chamber could be incorporated into a computer program. NAVFAC DM-39 (1982) provides guidance for pressure vessel design of hyperbaric chambers and the Pressure Vessel Handbook (1977) simplifies the calculations of pressure vessel design for desired conditions.

2) Fire protection and extinguishing systems along with other safety design criteria could be incorporated into a computer program. Additionally, electrical, utility, and communication systems could be considered. NAVFAC DM-39 (1982) provides guidance for these systems.

3) Different diving-gas mixtures could be investigated with additional facility requirements incorporated into the program. The NOAA Diving Manual (1991) lists some

alternatives to helium and research into the effects and advantages of these gases is ongoing.

4) In order to accurately calculate the density of diving-gas mixtures, the second and third virial coefficients need to be accurately determined. Although these coefficients exist for helium and oxygen, they have not been accurately determined for the mixtures. Texas A & M University has the facilities to accurately determine these coefficients if funding is available.

5) Heat transfer between the hyperbaric chamber and the environment is not considered in this program. A detailed study of materials and insulation would be necessary prior to incorporating it into a computer program.

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APPENDIX A
NOMENCLATURE

B - second virial coefficient, ft^3/mole
C - third virial coefficient, $\text{ft}^6/\text{mole}^2$
 CO_{2p} - carbon dioxide production, SCFM
 C_p - specific heat at constant pressure, BTU/lb-mole
D - fourth virial coefficient, $\text{ft}^9/\text{mole}^3$
d - working depth, feet of seawater (fsw)
 $d_{\max}$ - maximum allowable depth for a diving-gas mixture, fsw
 $d_{\min}$ - minimum allowable depth for a diving-gas mixture, fsw
H - molar enthalpy of moisture content at saturation,
BTU/mole dry gas
 H_a - moist-gas-mixture enthalpy at initial temperature, BTU/lb
 H_c - moist-gas-mixture enthalpy at coil temperature, BTU/lb
 H_1 - molar enthalpy of moisture content at initial conditions,
BTU/mole dry gas
 H_2 - molar enthalpy of moisture content at desired conditions,
BTU/mole dry gas
 lb_{CO_2} - carbon dioxide produced, lb
 lb_g - sodasorb required for absorption, lb
m - mass flowrate of carbon dioxide, lb/min
MRR - moisture removal rate, lb/day
MW - molecular weight of diving-gas mixture, lb/lb-mole
n - number of moles
 N_d - number of divers
 O_{2c} - oxygen consumption, SCFM

O_{2r} - oxygen required to sustain divers, SCFM
 P - absolute pressure, psia
 P_{max} - maximum allowable pressure for a diving-gas mixture, psia
 P_{min} - minimum allowable pressure for a diving-gas mixture, psia
 PP_{O_2} - partial pressure of oxygen, atm
 PCO_2 - partial pressure of carbon dioxide, atm
 P_s - vapor pressure of water in saturated moist air, psia
 $\%He_{ideal}$ - percentage of helium in ideal diving-gas mixture
 $\%O_{2ideal}$ - percentage of oxygen in ideal diving-gas mixture
 $\%O_{2max}$ - maximum acceptable oxygen percentage
 $\%O_{2min}$ - minimum acceptable oxygen percentage
 Q_d - energy required for dehumidification, BTU/min
 Q_r - energy required to reheat from coil to desired temperature, BTU/min
 Q_t - total energy required, BTU/min
 R - gas constant for CO_2 , 35.11 lb/lbmole-R
 RH_d - desired relative humidity, %
 RH_i - initial relative humidity, %
 R_q - respiratory quotient
 R_u - universal gas constant, 1544 ft-lb/lbmole-R
 S_{air} - ventilation rate of air at standard conditions, SCFM
 T - initial temperature, ° F
 t - time to reach 95% steady-state conditions, hr
 T_c - maximum coil temperature for dehumidification, ° F
 T_d - desired temperature, ° F

t_d - mission duration, hr
 U - internal energy, BTU
 V - volume, ft^3
 V_{air} - volumetric flowrate at depth, ft^3/min
 V_{ch} - volume of the chamber, ft^3
 V_1 - specific volume, ft^3/lb
 V_m - molar volume, ft^3/mole
 W_1 - humidity ratio at initial relative humidity, lb_w/lb_d
 W_2 - humidity ratio at desired relative humidity, lb_w/lb_w
 X_{He} - mole fraction of helium
 X_{O_2} - mole fraction of oxygen
 X_{w_s} - mole fraction of water at saturation,
 moles water vapor/mole dry gas
 X_{w1} - moisture mole fraction at initial conditions,
 moles water vapor/mole dry gas
 X_{w2} - moisture mole fraction at desired conditions,
 moles water vapor/mole dry gas

APPENDIX B
SOURCE CODE

C MAJOR REPORT - "A COMPUTER SIMULATION OF A HYPERBARIC
C CHAMBER ENVIRONMENT."

REAL VAR, DEPTH, PRESS, TFI, TRI, TFD, RHI, RHD,
+NUMDIV, CHVOL, FLOWRATE, DUR, VAR1, O2CONS, PERO2,
+PERHE, O2MIN, O2MAX, DMIN, DMAX, PSIAMIN, PSIAMAX, VAIR,
+SURAIR, O2REQ, TIME, MW, CP, DENS, BC, BF, XWS, XW1,
+XW2, H, H1, H2, HA, HC, CT, QD, QR, QT, MRR, AIR, LBCO2,
+LBS, CASES

C VAR = A VARIABLE TO DETERMINE WHETHER THE USER WISHES TO
C CALCULATE THE GAS MIXTURE BASED UPON DEPTH OR
C PRESSURE.
C DEPTH = A WORKING DEPTH USED TO CALCULATE THE DIVING-GAS
C MIXTURE IN FEET.
C PRESS = PRESSURE AT DEPTH IN PSIA.
C TFI = THE INITIAL TEMPERATURE OF THE CHAMBER IN DEGREES
C FARENHEIT.
C TRI = THE INITIAL TEMPERATURE OF THE CHAMBER IN DEGREES
C RANKINE.
C TFD = THE DESIRED TEMPERATURE OF THE CHAMBER IN DEGREES
C FARENHEIT.
C RHI = THE INITIAL RELATIVE HUMIDITY IN THE CHAMBER.
C RHD = THE DESIRED RELATIVE HUMIDITY IN THE CHAMBER.
C NUMDIV = NUMBER OF DIVERS IN THE CHAMBER.
C CHVOL = THE INTERNAL VOLUME OF THE CHAMBER IN CUBIC
C FEET.
C FLOWRATE = THE FLOWRATE INSIDE THE CHAMBER USED FOR
C RECIRCULATING THE DIVING-GAS MIXTURE WHEN CO2
C SCRUBBERS ARE USED.
C DUR = THE MISSION DURATION IN HOURS.
C VAR1 = A VARIABLE USED TO DETERMINE THE WORKING
C CONDITIONS.
C O2CONS = OXYGEN CONSUMPTION IN CUBIC FEET PER MINUTE.
C PERO2 = THE PERCENT OF OXYGEN IN THE DIVING-GAS MIXTURE.
C PERHE = THE PERCENT OF HELIUM IN THE DIVING-GAS MIXTURE.
C O2MIN = MINIMUM ACCEPTABLE OXYGEN PERCENTAGE IN THE
C DIVING-GAS.
C O2MAX = MAXIMUM ACCEPTABLE OXYGEN PERCENTAGE IN THE
C DIVING-GAS.
C DMIN = THE MINIMUM DEPTH IN FEET FOR WHICH A GIVEN
C DIVING-GAS CAN BE USED.
C DMAX = THE MAXIMUM DEPTH IN FEET FOR WHICH A GIVEN
C DIVING-GAS CAN BE USED.
C PSIAMIN = THE MINIMUM PRESSURE IN PSIA FOR WHICH A GIVEN
C DIVING-GAS CAN BE USED.
C PSIAMAX = THE MAXIMUM PRESSURE IN PSIA FOR WHICH A GIVEN
C DIVING-GAS CAN BE USED.
C VAIR = VENTILATION RATE AT DEPTH IN CUBIC FEET PER
C MINUTE.
C SURAIR = VENTILATION RATE AT THE SURFACE IN STANDARD
C CUBIC FEET PER MINUTE.

C O2REQ = OXYGEN REQUIRED TO SUSTAIN DIVERS IN STANDARD
 C CUBIC FEET PER MINUTE IF CO2 ABSORBERS ARE USED.
 C TIME = THE TIME REQUIRED FOR THE CHAMBER TO REACH 99%
 C STEADY-STATE CONDITIONS.
 C MW = THE MOLECULAR WEIGHT OF THE DIVING-GAS MIXTURE
 C (LB/LB-MOLE).
 C CP = THE SPECIFIC HEAT OF THE DIVING-GAS MIXTURE
 C (BTU/MOLE).
 C DENS = THE DENSITY OF THE DIVING-GAS MIXTURE (LB/CU FT).
 C BC = THE SECOND VIRIAL COEFFICIENT (CU CM/G-MOLE).
 C BF = THE SECOND VIRIAL COEFFICIENT (CU FT/LB-MOLE).
 C XWS = THE MOISTURE MOLE FRACTION OF WATER VAPOR AT
 C SATURATION (MOLES WATER VAPOR/MOLE DRY GAS).
 C XW1 = THE MOISTURE MOLE FRACTION AT THE INITIAL RELATIVE
 C HUMIDITY.
 C XW2 = THE MOISTURE MOLE FRACTION AT THE DESIRED RELATIVE
 C HUMIDITY.
 C H = THE MOLAR ENTHALPY OF MOISTURE CONTENT AT SATURATION
 C (BTU/MOLE DRY GAS).
 C H1 = THE MOLAR ENTHALPY OF MOISTURE CONTENT AT THE
 C INITIAL R.H.
 C H2 = THE MOLAR ENTHALPY OF MOISTURE CONTENT AT THE
 C DESIRED R.H.
 C HA = THE MOIST-GAS-MIXTURE ENTHALPY AT INITIAL
 C CONDITIONS (BTU/LB DRY GAS).
 C HC = THE MOIST-GAS-MIXTURE ENTHALPY AT DESIRED
 C CONDITIONS.
 C CT = THE COIL TEMPERATURE REQUIRED FOR DEHUMIDIFICATION
 C IN DEGREES FARENHEIT.
 C QD = THE ENERGY REQUIRED FOR DEHUMIDIFICATION (BTU/MIN).
 C QR = THE ENERGY REQUIRED FOR REHEAT (BTU/MIN).
 C QT = THE TOTAL ENERGY REQUIRED FOR DEHUMIDIFICATION AND
 C REHEAT (BTU/MIN).
 C MRR = THE REQUIRED MOISTURE REMOVAL RATE FOR THE
 C DEHUMIDIFICATION PROCESS (LB/DAY).
 C LBCO2 = AMOUNT OF CO2 PRODUCED (LBS).
 C AIR = A VARIABLE TO DETERMINE WHETHER OR NOT AIR IS
 C BEING USED AS THE DIVING-GAS.
 C LBS = AMOUNT OF SODASORB REQUIRED FOR CO2 ABSORPTION
 C (LBS).
 C CASES = THE NUMBER OF CASES TO BE CALCULATED.

C . THIS PORTION OF THE PROGRAM WILL ALLOW THE USER TO INPUT
 C THE NECESSARY PARAMETERS FROM A DATA FILE.

OPEN (UNIT=3, FILE='VAR.DAT', STATUS='OLD')
 OPEN (UNIT=4, FILE='OUTPUT.DAT', STATUS='UNKNOWN')

READ (3,*) CASES

DO 500 I = 1, CASES

```
READ (3,*) VAR, DEPTH, TFI, TFD, RHI, RHD  
READ (3,*) NUMDIV, CHVOL, FLOWRATE, DUR, VAR1
```

```
IF (VAR.EQ.0) THEN
```

```
    CALL CONVERT(DEPTH, PRESS)
```

```
    GO TO 10
```

```
ELSE
```

```
    PRESS=DEPTH
```

```
    GO TO 10
```

```
ENDIF
```

```
10 TRI=TFI+459.67
```

```
IF (VAR1.EQ.1) THEN
```

```
    O2CONS=0.5/28.3
```

```
ELSEIF (VAR1.EQ.2) THEN
```

```
    O2CONS=0.7/28.3
```

```
ELSEIF (VAR1.EQ.3) THEN
```

```
    O2CONS=1.5/28.3
```

```
ELSEIF (VAR1.EQ.4) THEN
```

```
    O2CONS=2.0/28.3
```

```
ELSE
```

```
    O2CONS=3.0/28.5
```

```
ENDIF
```

```
C THIS PORTION OF THE PROGRAM CALCULATES THE IDEAL AND  
C ACCEPTABLE DIVING-GAS MIXTURES.
```

```
CALL GASMIX (PRESS,O2MIN,O2MAX)
```

```
IF (O2MAX.GE.21.0) THEN
```

```
    AIR=1
```

```
    PERO2=21.0
```

```
ELSE
```

```
    AIR=0
```

```
    IF (O2MAX.GE.15.0) THEN
```

```
        PERO2=15.0
```

```
    ELSEIF (O2MAX.GE.10.0) THEN
```

```
        PERO2=10.0
```

```
    ELSEIF (O2MAX.GE.5.0) THEN
```

```
        PERO2=5.0
```

```
    ELSEIF (O2MAX.GE.3.0) THEN
```

```

        PERO2=3.0
    ELSEIF (O2MAX.GE.1.0) THEN
        PERO2=1.0
    ELSEIF (O2MAX.GE.0.5) THEN
        PERO2=0.5
    ELSE
        PERO2=0.1
    ENDIF

```

```

    PERHE=100.0-PERO2

```

```

    CALL GASRANGE(PERO2,DMIN,DMAX,PSIAMIN,PSIAMAX)

```

```

ENDIF

```

```

C   THIS PORTION OF THE PROGRAM WILL CALCULATE THE REQUIRED
C   VENTILATION RATE WITH OR WITHOUT CARBON DIOXIDE
C   ABSORBERS.

```

```

    IF (AIR.EQ.1) THEN

```

```

        CALL FREERATE(O2CONS,NUMDIV,TRI,PRESS,VAIR,SURAIR)

```

```

    ELSE

```

```

        CALL ABSRATE(NUMDIV,O2REQ,O2CONS,DUR,LBCO2,LBS)

```

```

    ENDIF

```

```

    CALL STSTATE(CHVOL,O2CONS,NUMDIV,TRI,TIME)

```

```

C   THIS PORTION OF THIS PROGRAM CALCULATES THE PROPERTIES
C   OF THE DIVING-GAS MIXTURE.

```

```

    CALL MOLWT(PERO2 MW,AIR)

```

```

    CALL SPECHEAT(PERO2,CP,AIR)

```

```

    CALL DENSITY(PERO2,TRI,PRESS,MW,DENS,BC,BF,AIR)

```

```

C   THIS PORTION OF THE PROGRAM DETERMINES THE PSYCHROMETRIC
C   PROPERTIES.

```

```

    CALL PSYCHART(TFI,TRI,PRESS,XWS.H)

```

```

    CALL XWSH(RHI,RHD,XWS,XW1,XW2,H,H1,H2)

```

```

    CALL COILTEMP(XW2,PRESS,CT)

```

```

    CALL MGMTENTH(TFI,CT,CP,H1,H2,MW,HA,HC)

```



```

C   THIS PORTION OF THE PROGRAM CALCULATES THE ENERGY
C   REQUIREMENTS FOR DEHUMIDIFICATION AND REHEAT ALONG WITH
C   MOISTURE REMOVAL REQUIREMENTS.

```

```

    CALL ENERGY(DENS,AIR,VAIR,FLOWRATE,HA,HC,TFD,CT,CP,MW
+QD,QR,QT)

```

```

    CALL MOISTREM(XW1,XW2,AIR,FLOWRATE,MW,VAIR,DENS,MRR)

```

```

C   THIS PORTION OF THE PROGRAM PRODUCES THE OUTPUT.

```

```

    IF (AIR.EQ.0) THEN

```

```

        WRITE (4,12)
12    FORMAT (1X,'*****
+*****')

```

```

        WRITE (4,15) I
15    FORMAT (35X,'CASE ',I2)

```

```

        WRITE (4,20)
20    FORMAT (1X,'*****
+*****')

```

```

        WRITE (4,25)
25    FORMAT (25X,'"HYPERBARIC CHAMBER SIMULATION"')

```

```

        WRITE (4,30)
30    FORMAT (1X,'*****
+*****')

```

```

        WRITE (4,35)
35    FORMAT (5X,'INPUT CONDITIONS:')

```

```

        WRITE (4,40) PRESS
40    FORMAT (5X,'PRESSURE (PSIA):',24X,1F6.1)

```

```

        WRITE (4,45) TFI,TFD
45    FORMAT (5X,'INITIAL/DESIRED TEMP (DEG F):',9X,1F4.1,'/',
+1F4.1)

```

```

        WRITE (4,50) RHI,RHD
50    FORMAT (5X,'INITIAL/DESIRED REL HUM (%)',10X,1F4.1,'/',
+1F4.1)

```

```

        WRITE (4,55) NUMDIV,VAR1
55    FORMAT (5X,'# OF DIVERS/WORKING CONDITIONS:',7X,1F4.1,
+'/',1F2.0)

```

```

        WRITE (4,60) CHVOL
60    FORMAT (5X,'CHAMBER VOLUME (CU FT):',17X,1F6.1)

```

```

70      WRITE (4,70) FLOWRATE
      FORMAT (5X,'FLOW RATE (CU FT/MIN):',18X,1F6.1)

      WRITE (4,75) DUR
75      FORMAT (5X,'MISSION DURATION (HRS):',17X,1F6.1)

      WRITE (4,100)
100     FORMAT (1X,'*****')
      +*****')

      WRITE (4,105)
105     FORMAT (5X,'OUTPUT:')

      WRITE (4,110) PERHE,PERO2
110     FORMAT (5X,'DIVING-GAS MIXTURE (%HE/%O2):',9X,1F4.1,
      + '/' ,1F4.1)

      WRITE (4,115) DMIN,DMAX
115     FORMAT (5X,'DIVING-GAS MIXTURE RANGE (FSW):',7X,1F6.1,
      + '/' ,1F6.1)

      WRITE (4,120) O2REQ
120     FORMAT (5X,'OXYGEN REQUIRED (SCFM):',18X,1F8.4)

      WRITE (4,125) LBCO2
125     FORMAT (5X,'CO2 PRODUCED (LB):',22X,1F6.1)

      WRITE (4,130) LBS
130     FORMAT (5X,'SODASORB REQUIRED:',22X,1F6.1)

      WRITE (4,135) TIME
135     FORMAT (5X,'TIME TO 95% STEADY STATE (HRS):',9X,1F6.1)

      WRITE (4,140) MW
140     FORMAT (5X,'MOLECULAR WEIGHT (LB/MOLE):',13X,1F8.3)

      WRITE (4,145) DENS
145     FORMAT (5X,'GAS MIXTURE DENSITY (LB/CU FT):',9X,1F10.5)

      WRITE (4,150) CT
150     FORMAT (5X,'MAXIMUM COIL TEMPERATURE (DEG F):',7X,1F6.1)

      WRITE (4,155) QD
155     FORMAT (5X,'DEHUMIDIFICATION ENERGY (BTU/MIN):',6X,
      +1F6.1)

      WRITE (4,160) QR
160     FORMAT (5X,'REHEAT ENERGY (BTU/MIN):',16X,1F6.1)

      WRITE (4,165) QT
165     FORMAT (5X,'ENERGY REQUIREMENTS (BTU/MIN):',10X,1F6.1)

```

```

WRITE (4,170) MRR
170  FORMAT (5X,'MOISTURE REMOVAL RATE (LB/DAY):',9X,1F6.1)

WRITE (4,175)
175  FORMAT (1X,'*****')
+*****')

ELSE

WRITE (4,200)
200  FORMAT (1X,'*****')
+*****')

WRITE (4,205)
205  FORMAT (25X,'"HYPERBARIC CHAMBER SIMULATION"')

WRITE (4,210)
210  FORMAT (1X,'*****')
+*****')

WRITE (4,215)
215  FORMAT (5X,'INPUT CONDITIONS:')

WRITE (4,220) PRESS
220  FORMAT (5X,'PRESSURE (PSIA):',24X,1F6.1)

WRITE (4,225) TFI,TFD
225  FORMAT (5X,'INITIAL/DESIRED TEMP (DEG F):',9X,1F4.1,'/',
+1F4.1)

WRITE (4,230) RHI,RHD
230  FORMAT (5X,'INITIAL/DESIRED REL HUM (%):',10X,1F4.1,'/',
+1F4.1)

WRITE (4,235) NUMDIV,VARI
235  FORMAT (5X,'# OF DIVERS/WORKING CONDITIONS:',7X,1F4.1,
+'/',1F2.0)

WRITE (4,240) CHVOL
240  FORMAT (5X,'CHAMBER VOLUME (CU FT):',17X,1F6.1)

WRITE (4,245)
245  FORMAT (1X,'*****')
+*****')

WRITE (4,250)
250  FORMAT (5X,'OUTPUT:')

WRITE (4,255)
255  FORMAT (5X,'DIVING-GAS MIXTURE:',23X,'AIR')

```

```

      WRITE (4,260)
260   FORMAT (5X,'DIVING-GAS MIXTURE RANGE (FSW):',10X,
      + '0.0/60.0')

      WRITE (4,265) VAIR
265   FORMAT (5X,'FREE VENTILATION RATE AT DEPTH (CFM):',3X,
      + 1F6.1)

      WRITE (4,270) SURAIR
270   FORMAT (5X,'FREE VENTILATION RATE (SCFM):',11X,1F6.1)

      WRITE (4,275) TIME
275   FORMAT (5X,'TIME TO 95% STEADY-STATE (HRS):',9X,1F6.1)

      WRITE (4,280) MW
280   FORMAT (5X,'MOLECULAR WEIGHT (LB/MOLE):',15X,1F4.1)

      WRITE (4,285) DENS
285   FORMAT (5X,'DENSITY OF AIR (LB/CU FT):',14X,1F10.5)

      WRITE (4,290) CT
290   FORMAT (5X,'MAXIMUM COIL TEMPERATURE (DEG F):',7X,1F6.1)

      WRITE (4,295) QD
295   FORMAT (5X,'DEHUMIDIFICATION ENERGY (BTU/MIN):',6X,
      + 1F6.1)

      WRITE (4,300) QR
300   FORMAT (5X,'REHEAT ENERGY (BTU/MIN):',16X,1F6.1)

      WRITE (4,305) QT
305   FORMAT (5X,'ENERGY REQUIREMENTS (BTU/MIN):',10X,1F6.1)

      WRITE (4,310) MRR
310   FORMAT (5X,'MOISTURE REMOVAL RATE (LB/DAY):',9X,1F6.1)

      WRITE (4,315)
315   FORMAT (1X,'*****
      +*****')

      ENDOF

500   CONTINUE

      END

```

```

C -----
SUBROUTINE CONVERT(DEPTH,PRESS)

C THIS SUBROUTINE CONVERTS A WORKING DEPTH IN FEET TO A
C PRESSURE IN PSIA.

REAL DEPTH, PRESS

C DEPTH = A WORKING DEPTH IN FEET.
C PRESS = A CONVERTED PRESSURE IN PSIA.

PRESS=((DEPTH+33.06633)/33.06633)*14.696

END

C -----

SUBROUTINE GASMIX(PRESS,O2MIN,O2MAX)

C THIS SUBROUTINE CALCULATES AN ACCEPTABLE DIVING GAS
C MIXTURE BASED UPON A MINIMUM OXYGEN PARTIAL PRESSURE OF
C 0.16 ATM AND A MAXIMUM OXYGEN PARTIAL PRESSURE OF 0.6
C ATM.

REAL PRESS, PATM, O1MIN, O2MIN, O1MAX, O2MAX

C PRESS = THE CHAMBER PRESSURE IN PSIA.
C PATM = THE CHAMBER PRESSURE IN ATM.
C O1MIN = MINIMUM ACCEPTABLE OXYGEN FRACTION IN THE
C DIVING-GAS.
C O2MIN = MINIMUM ACCEPTABLE OXYGEN PERCENTAGE IN THE
C DIVING-GAS.
C O1MAX = MAXIMUM ACCEPTABLE OXYGEN FRACTION IN THE
C DIVING-GAS.
C O2MAX = MAXIMUM ACCEPTABLE OXYGEN PERCENTAGE IN THE
C DIVING-GAS.

PATM=PRESS/14.696
O1MIN=0.16/PATM
O2MIN=O1MIN*100.0
O1MAX=0.6/PATM
O2MAX=O1MAX*100.0

END

```

```

C -----
SUBROUTINE GASRANGE(PERO2,DMIN,DMAX,PSIAMIN,PSIAMAX)

C THIS SUBROUTINE CALCULATES A DEPTH AND PRESSURE RANGE
C FOR A GIVEN DIVING-GAS MIXTURE.

REAL PERO2, PMIN, DMIN, PMAX, DMAX, PSIAMIN, PSIAMAX

C PERO2 = THE PERCENTAGE OF OXYGEN IN THE DIVING-GAS
C MIXTURE.
C PMIN = THE MINIMUM PRESSURE (ATM) BASED UPON AN OXYGEN
C PARTIAL PRESSURE OF 0.16 ATM.
C DMIN = THE MINIMUM DEPTH (FT) FOR A GIVEN DIVING-GAS.
C PMAX = THE MAXIMUM PRESSURE (ATM) BASED UPON AN OXYGEN
C PARTIAL PRESSURE OF 0.6 ATM.
C DMAX = THE MAXIMUM DEPTH (FT) FOR A GIVEN DIVING-GAS.
C PSIAMIN = THE MINIMUM PRESSURE (PSIA) FOR A GIVEN
C DIVING-GAS.
C PSIAMAX = THE MAXIMUM PRESSURE (PSIA) FOR A GIVEN
C DIVING-GAS.

      PMIN=16.0/PERO2
      DMIN=PMIN*33.06633-33.06633
      PMAX=60.0/PERO2
      DMAX=PMAX*33.06633-33.06633
      PSIAMIN=14.696*PMIN
      PSIAMAX=14.696*PMAX

      END

C -----
SUBROUTINE FREERATE(O2CONS,NUMDIV,TRI,PRESS,VAIR,SURAIR)

C THIS SUBROUTINE CALCULATES THE REQUIRED VENTILATION RATE
C FOR THE CHAMBER WITHOUT CARBON DIOXIDE ABSORBERS.

REAL O2CONS, NUMDIV, TRI, PRESS, VAIR, SURAIR, CO2PROD,
+MFLOW

C O2CONS = OXYGEN CONSUMPTION IN CUBIC FEET PER MINUTE.
C NUMDIV = THE NUMBER OF DIVERS IN THE CHAMBER.
C TRI = THE INITIAL CHAMBER TEMPERATURE IN DEGREES
C RANKINE.
C PRESS = THE CHAMBER PRESSURE IN PSIA.
C VAIR = THE VENTILATION RATE AT DEPTH (CU FT/MIN).
C SURAIR = THE VENTILATION RATE AT THE SURFACE (SCFM).
C CO2PROD = THE TOTAL AMOUNT OF CARBON DIOXIDE PRODUCED
C (CU FT/MIN).
C MFLOW = THE MASS FLOW RATE OF CARBON DIOXIDE (LB/MIN).

```

```

CO2PROD=0.9*O2CONS*NUMDIV
MFLOW=0.11372474*CO2PROD
VAIR=3.31817426*MFLOW*TRI
SURAIR=(VAIR*PRESS*529.67)/(14.696*TRI)

```

END

C -----

SUBROUTINE ABSRATE(NUMDIV,O2REQ,O2CONS,DUR,LBCO2,LBS)

C THIS SUBROUTINE CALCULATES THE REQUIRED VENTILATION RATE
C OF THE CHAMBER IF CARBON DIOXIDE ABSORBERS ARE UTILIZED.

REAL NUMDIV, O2REQ, O2CONS, DUR, LBCO2, MFLOW, LBS,
+CO2PROD

C NUMDIV = THE NUMBER OF DIVERS IN THE CHAMBER.
C O2REQ = THE AMOUNT OF PURE OXYGEN REQUIRED (SCFM).
C O2CONS = THE OXYGEN CONSUMPTION (SCFM).
C DUR = THE MISSION DURATION IN HOURS.
C LBCO2 = THE AMOUNT OF CO2 PRODUCED (LB).
C MFLOW = THE MASS FLOWRATE OF CARBON DIOXIDE (LB/MIN).
C CO2PROD = CARBON DIOXIDE PRODUCTION (CU FT/MIN).
C LBS = AMOUNT OF SODASORB REQUIRED FOR CO2 ABSORPTION
C (LBS).

```

O2REQ=NUMDIV*O2CONS
CO2PROD=0.9*O2CONS*NUMDIV
MFLOW=0.11372474*CO2PROD
LBCO2=MFLOW*60.0*DUR
LBS=LBCO2/0.245

```

END

C -----

SUBROUTINE STSTATE(CHVOL,O2CONS,NUMDIV,TRI,TIME)

C THIS SUBROUTINE CALCULATES THE TIME REQUIRED FOR THE
C CHAMBER TO REACH A 95% STEADY-STATE CONDITION.

REAL CHVOL, O2CONS, NUMDIV, TRI, TIME, CO2PROD, MFLOW,
+VAIR

C CHVOL = THE INTERIOR CHAMBER VOLUME (CUBIC FEET).
C O2CONS = OXYGEN CONSUMPTION (CU FT/MIN).
C NUMDIV = THE NUMBER OF DIVERS IN THE CHAMBER.

C TRI = THE INITIAL TEMPERATURE OF THE CHAMBER IN DEGREES
C RANKINE.

C TIME = THE TIME REQUIRED TO REACH 99% STEADY-STATE
C (HRS).

```

C      CO2PROD = THE CARBON DIOXIDE PRODUCTION (CU FT/MIN) .
C      MFLOW = THE MASS FLOWRATE OF CARBON DIOXIDE (LB/MIN) .
C      VAIR = THE VENTILATION RATE AT DEPTH (CU FT/MIN) .

```

```

      CO2PROD=0.9*O2CONS*NUMDIV
      MFLOW=0.11372474*CO2PROD
      VAIR=3.31817426*MFLOW*TRI
      TIME=(-0.0167*CHVOL/VAIR)*LOG(1.0-(0.2863*VAIR)
+      /(MFLOW*TRI))

```

```

      END

```

```

C      -----

```

```

      SUBROUTINE MOLWT(PERO2,MW,AIR)

```

```

C      THIS SUBROUTINE CALCULATES THE MOLECULAR WEIGHT OF THE
C      DIVING-GAS MIXTURE.

```

```

      REAL PERO2, MW, XO2, XHE, AIR

```

```

C      PERO2 = THE PERCENTAGE OF OXYGEN IN THE DIVING-GAS
C      MIXTURE.
C      MW = THE MOLECULAR WEIGHT OF THE MIXTURE (LB/LB-MOLE) .
C      XO2 = THE MOLE FRACTION OF OXYGEN IN THE MIXTURE.
C      XHE = THE MOLE FRACTION OF HELIUM IN THE MIXTURE.
C      AIR = A VARIABLE TO DETERMINE IF THE DIVING-GAS IS AIR.

```

```

      IF (AIR.EQ.1) THEN

```

```

          MW=29.0

```

```

      ELSE

```

```

          XO2=PERO2/100.0
          XHE=1.0-XO2
          MW=(XO2*32.00)+(XHE*4.0026)

```

```

      ENDIF

```

```

      END

```

```

C      -----

```

```

      SUBROUTINE SPECHEAT(PERO2,CP,AIR)

```

```

C      THIS SUBROUTINE CALCULATES THE SPECIFIC HEAT OF THE
C      DIVING-GAS MIXTURE.

```

```

      REAL PERO2, CP, XO2, XHE, AIR

```

```

C      PERO2 = THE PERCENTAGE OF OXYGEN IN THE DIVING-GAS
C      MIXTURE.

```



```

C      CP = THE SPECIFIC HEAT OF THE DIVING-GAS MIXTURE
C          (BTU/MOLE) .
C      XO2 = THE MOLE FRACTION OF OXYGEN IN THE MIXTURE.
C      XHE = THE MOLE FRACTION OF HELIUM IN THE MIXTURE.
C      AIR = A VARIABLE TO DETERMINE IF THE DIVING-GAS IS AIR.

```

```

      IF (AIR.EQ.1) THEN

```

```

          CP=6.95

```

```

      ELSE

```

```

          XO2=PERO2/100.0

```

```

          XHE=1.0-XO2

```

```

          CP=(XO2*6.95)+(XHE*4.965)

```

```

      ENDIF

```

```

      END

```

```

C      -----

```

```

      SUBROUTINE DENSITY(PERO2,TRI,PRESS,MW,DENS,BC,BF,AIR)

```

```

C      THIS SUBROUTINE CALCULATES THE DENSITY OF THE DIVING-GAS
C      MIXTURE.

```

```

      REAL PERO2, TRI, PRESS, MW, DENS, BC, BF, CONST, MOLVOL,
      +AIR

```

```

C      PERO2 = THE PERCENTAGE OF OXYGEN IN THE DIVING-GAS
C              MIXTURE.

```

```

C      TRI = THE INITIAL CHAMBER TEMPERATURE IN DEGREES
C            RANKINE.

```

```

C      PRESS= THE INITIAL CHAMBER PRESSURE IN PSIA.

```

```

C      MW = THE MOLECULAR WEIGHT OF THE DIVING-GAS MIXTURE
C           (LB/LB-MOLE) .

```

```

C      DENS = THE DENSITY OF THE DIVING-GAS MIXTURE (LB/CU
C            FEET) .

```

```

C      BC = THE SECOND VIRIAL COEFFICIENT (CU CM/MOLE) .

```

```

C      BF = THE SECOND VIRIAL COEFFICIENT (CU FT/MOLE) .

```

```

C      CONST = RT/P

```

```

C      MOLVOL = MOLAR VOLUME (CU FT/MOLE)

```

```

C      AIR = A VARIABLE TO DETERMINE IF THE DIVING-GAS IS AIR.

```

```

      IF (AIR.EQ.1) THEN

```

```

          DENS=(MW*PRESS*144.C)/(1544.0*TRI)

```

```

      ELSE

```

```

          XO2=PERO2/100.0

```

```

          XHE=1.0-XO2

```

```

BC=(11.44*XHE**2)-(8.8*XHE*XO2)-(16.24*XO2**2)
BF=BC*3.5315E-05*454.0
CONST=(1544.0*TRI)/(PRESS*144.0)
MOLVOL=(CONST+SQRT((CONST**2)+(4.0*CONST*BF)))/2.0
DENS=MW/MOLVOL

```

```

ENDIF

```

```

END

```

```

C

```

```

-----
SUBROUTINE PSYCHART(TFI,TRI,PRESS,XWS,H)

```

```

C   THIS SUBROUTINE CALCULATES THE MOISTURE MOLE FRACTION
C   AND ENTHALPY OF MOISTURE UTILIZING THE PSYCHROMETRIC
C   CHART.

```

```

REAL TFI, TRI, PRESS, XWS, H, PS, DPS, VL

```

```

C   TFI = THE INITIAL CHAMBER TEMPERATURE IN DEGREES
C   FARENHEIT.
C   TRI = THE INITIAL CHAMBER TEMPERATURE IN DEGREES
C   RANKINE.
C   PRESS = THE INITIAL CHAMBER PRESSURE IN PSIA.
C   XWS = THE MOISTURE MOLE FRACTION (MOLES WATER VAPOR/MOLE
C   DRY GAS).
C   H = THE ENTHALPY OF MOISTURE CONTENT (BTU/MOLE DRY GAS).
C   PS = THE SATURATION PRESSURE OF WATER (PSIA).
C   DPS = THE CHANGE IN SATURATION PRESSURE OF WATER FOR
C   PRESSURES ABOVE 100 PSIA.
C   VL = THE SPECIFIC VOLUME OF THE SATURATED LIQUID (CU
C   FT/LB).

```

```

C   THIS PORTION OF THE SUBROUTINE CALCULATES THE SATURATION
C   PRESSURE OF WATER GIVEN THE DRY BULB TEMPERATURE.

```

```

PS=(1.9285E-11*TFI**5)+(9.8683E-10*TFI**4)+
+(3.3193E-07*TFI**3)+(1.9916E-05*TFI**2)+
+(1.0488E-03*TFI)+2.2080E-02

```

```

C   THIS PORTION OF THE SUBROUTINE CORRECTS THE SATURATION
C   PRESSURE FOR PRESSURES ABOVE 100 PSIA USING POYNTING'S
C   EQUATION.

```

```

IF (PRESS.GT.100.0) THEN
  IF (TFI.GT.32.0.AND.TFI.LE.52.0) THEN
    VL=0.01602
  ELSEIF (TFI.GT.52.0.AND.TFI.LE.60.0) THEN
    VL=0.01603
  ELSEIF (TFI.GT.60.0.AND.TFI.LE.66.0) THEN
    VL=0.01604

```

```

ELSEIF (TFI.GT.66.0.AND.TFI.LE.71.0) THEN
  VL=0.01605
ELSEIF (TFI.GT.71.0.AND.TFI.LE.76.0) THEN
  VL=0.01606
ELSEIF (TFI.GT.76.0.AND.TFI.LE.80.0) THEN
  VL=0.01607
ELSEIF (TFI.GT.80.0.AND.TFI.LE.84.0) THEN
  VL=0.01608
ELSEIF (TFI.GT.84.0.AND.TFI.LE.87.0) THEN
  VL=0.01609
ELSEIF (TFI.GT.87.0.AND.TFI.LE.91.0) THEN
  VL=0.01610
ELSEIF (TFI.GT.91.0.AND.TFI.LE.94.0) THEN
  VL=0.01611
ELSEIF (TFI.GT.94.0.AND.TFI.LE.97.0) THEN
  VL=0.01612
ELSEIF (TFI.GT.97.0.AND.TFI.LE.100.0) THEN
  VL=0.01613
ELSEIF (TFI.GT.100.0) THEN
  VL=0.01614
ENDIF

```

```

DPS=(1.67876*PS*VL*PRESS)/TRI
PS=PS+DPS

```

```

GO TO 40

```

```

ELSE

```

```

GO TO 40

```

```

ENDIF

```

```

40  XWS=PS/(PRESS-PS)
    H=20000.0*XWS

```

```

END

```

```

C

```

```

SUBROUTINE XWSH(RHI,RHD,XWS,XW1,XW2,H,H1,H2)

```

```

C  THIS SUBROUTINE CALCULATES THE INITIAL AND DESIRED
C  MOISTURE MOLE FRACTIONS AND MOLAR ENTHALPIES.

```

```

REAL RHI, RHD, XWS, XW1, XW2, H, H1, H2, RH1, RH2

```

```

C  RHI = THE INITIAL RELATIVE HUMIDITY IN THE CHAMBER IN
C  PERCENT.
C  RHD = THE DESIRED RELATIVE HUMIDITY IN THE CHAMBER IN
C  PERCENT.
C  XWS = THE MOISTURE MOLE FRACTION FOR WATER VAPOR AT
C  SATURATION.

```

```

C   XW1 = THE MOISTURE MOLE FRACTION AT THE INITIAL RELATIVE
C   HUMIDITY.
C   XW2 = THE MOISTURE MOLE FRACTION AT THE DESIRED RELATIVE
C   HUMIDITY.
C   H = THE MOLAR ENTHALPY OF MOISTURE CONTENT AT
C   SATURATION.
C   H1 = THE MOLAR ENTHALPY OF MOISTURE CONTENT AT THE
C   INITIAL R.H.
C   H2 = THE MOLAR ENTHALPY OF MOISTURE CONTENT AN THE
C   DESIRED R.H.
C   RH1 = THE INITIAL RELATIVE HUMIDITY IN THE CHAMBER
C   (FRACTION).
C   RH2 = THE DESIRED RELATIVE HUMIDITY IN THE CHAMBER
C   (FRACTION).

```

```

      RH1=RH1/100.0
      RH2=RH2/100.0
      XW1=RH1*XWS
      XW2=RH2*XWS
      H1=RH1*H
      H2=RH2*H

```

```

      END

```

```

C

```

```

      SUBROUTINE COILTEMP(XW2,PRESS,CT)

```

```

C   THIS SUBROUTINE CALCULATES THE COIL TEMPERATURE REQUIRED
C   FOR DEHUMIDIFICATION TO A DESIRED RELATIVE HUMIDITY.

```

```

      REAL XW2, PRESS, PS, CT

```

```

C   XW2 = THE MOISTURE MOLE FRACTION AT THE DESIRED RELATIVE
C   HUMIDITY.
C   PRESS = THE INITIAL CHAMBER PRESSURE (PSIA).
C   PS = THE SATURATION PRESSURE OF WATER (PSIA).
C   CT = THE COIL TEMPERATURE REQUIRED FOR DEHUMIDIFICATION.

```

```

      PS=(XW2*PRESS)/(1.0+XW2)

```

```

      CT=(2.4135E02*PS**5)-(8.4538E02*PS**4)+
      +(1.1635E03*PS**3)-(8.1910E02*PS**2)+
      +(3.5407E02*PS)+7.0106

```

```

      END

```

```

C -----
SUBROUTINE MGMTENTH(TFI,CT,CP,H1,H2,MW,HA,HC)

C THIS SUBROUTINE CALCULATES THE MOIST-GAS-MIXTURE
C ENTHALPIES AT THE INITIAL CONDITIONS AND COIL
C TEMPERATURE.

REAL TFI, CT, CP, H1, H2, MW, HA, HC

C TFI = THE INITIAL CHAMBER TEMPERATURE IN DEGREES
C FARENHEIT.
C CT = THE REQUIRED COIL TEMPERATURE FOR DEHUMIDIFICATION
C (F).
C CP = THE SPECIFIC HEAT OF THE GAS MIXTURE (BTU/MOLE).
C H1 = THE MOLAR ENTHALPY OF MOISTURE CONTENT AT THE
C INITIAL R.H.
C H2 = THE MOLAR ENTHALPY OF MOISTURE CONTENT AT THE
C DESIRED R.H.
C MW = THE MOLECULAR WEIGHT OF THE MIXTURE (LB/LB-MOLE).
C HA = THE MOIST-GAS-MIXTURE ENTHALPY AT THE INITIAL
C CONDITIONS.
C HC = THE MOIST-GAS-MIXTURE ENTHALPY AT THE DESIRED
C CONDITIONS.

HA=((CP*TFI)+H1)/MW
HC=((CP*CT)+H2)/MW

END

C -----
SUBROUTINE ENERGY(DENS,AIR,VAIR,FLOWRATE,HA,HC,TFD,CT,
+CP,MW,QD,QR,QT)

C THIS SUBROUTINE CALCULATES THE ENERGY REQUIRED FOR
C DEHUMIDIFICATION AND REHEAT.

REAL DENS, AIR, VAIR, FLOWRATE, HA, HC, TFD, CT, CP, MW,
+QD, DH, QR, QT

C DENS = THE DENSITY OF THE DIVING-GAS MIXTURE (LB/CU FT).
C AIR = A VARIABLE TO DETERMINE IF THE DIVING-GAS IS AIR.
C VAIR = THE VENTILATION OR CIRCULATION RATE AT DEPTH (CU
C FT/MIN).
C FLOWRATE = THE CIRCULATION RATE (CU FT/MIN).

C HA = THE MOIST-GAS-MIXTURE ENTHALPY AT THE INITIAL
C CONDITIONS.
C HC = THE MOIST-GAS-MIXTURE ENTHALPY AT THE DESIRED
C CONDITIONS.
C TFD = THE DESIRED CHAMBER TEMPERATURE AFTER REHEAT (F).
C CT = THE COIL TEMPERATURE REQUIRED FOR DEHUMIDIFICATION

```

```

C      CP = THE SPECIFIC HEAT OF THE DIVING-GAS MIXTURE
C          (BTU/MOLE) .
C      MW = THE MOLECULAR WEIGHT OF THE MIXTURE (LB/LB-MOLE) .
C      QD = THE ENERGY REQUIRED FOR DEHUMIDIFICATION (BTU/MIN) .
C      DH = THE CHANGE IN ENTHALPY FROM THE COIL TEMPERATURE TO
C          THE DESIRED CHAMBER TEMPERATURE (BTU/MIN) .
C      QR = THE ENERGY REQUIRED FOR REHEAT (BTU/MIN) .
C      QT = THE TOTAL ENERGY REQUIRED DEHUMIDIFICATION AND
C          REHEAT (BTU/MIN) .

```

```

      IF (AIR.EQ.0) THEN
          VAIR=FLOWRATE

```

```

      ELSE
          VAIR=VAIR

```

```

      ENDIF

```

```

          QD=DENS*VAIR*(HA-HC)
          DH=CP*(TFD-CT)/MW
          QR=DENS*VAIR*DH
          QT=QD+QR

```

```

      END

```

```

C

```

```

      -----
      SUBROUTINE MOISTREM(XW1,XW2,AIR,FLOWRATE,MW,VAIR,
+DENS,MRR)

```

```

C      THIS SUBROUTINE CALCULATES THE MOISTURE REMOVAL RATE
C      REQUIRED FOR DEHUMIDIFICATION.

```

```

      REAL W1, W2, XW1, XW2, AIR, FLOWRATE, MW, VAIR, DENS,
+MRR

```

```

C      W1 = THE HUMIDITY RATIO AT THE INITIAL RELATIVE
C          HUMIDITY.
C      W2 = THE HUMIDITY RATIO AT THE DESIRED RELATIVE
C          HUMIDITY.
C      XW1 = THE MOISTURE MOLE FRACTION AT THE INITIAL RELATIVE
C          HUMIDITY.
C      XW2 = THE MOISTURE MOLE FRACTION AT THE DESIRED RELATIVE
C          HUMIDITY.
C      AIR = A VARIABLE TO DETERMINE IF THE DIVING-GAS IS AIR.
C      FLOWRATE = THE CIRCULATION RATE (CU FT/MIN) .
C      MW = THE MOLECULAR WEIGHT OF THE DIVING-GAS MIXTURE
C          (LB/LB-MOLE) .
C      VAIR = THE VENTILATION RATE AT DEPTH (CU FT/MIN) .
C      DENS = THE DENSITY OF THE DIVING-GAS MIXTURE (LB/CU FT) .
C      MRR = THE REQUIRED MOISTURE REMOVAL RATE FOR THE
C          DEHUMIDIFICATION PROCESS (LB/DAY) .

```

IF (AIR.EQ.0) THEN
VAIR=FLOWRATE

ELSE

VAIR=VAIR

ENDIF

W1=XW1*(18.0158/MW)

W2=XW2*(18.0158/MW)

MRR=(W1-W2)*VAIR*DENS*1440.0

END

C
