ENGINEERING EVALUATION
STUDY OF
ENVIRONMENTAL CONDITIONING SYSTEMS
FOR
HIGH PRESSURE RESEARCH VESSELS

FINAL REPORT

Contract No. N00014-72-C-0125

Office of Naval Research
U.S. Navy

By

John M. Canty
Edward H. Lanphier
Richard A. Morin

28 June 1972

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High Pressure Laboratory
Department of Physiology
State University of New York at Buffalo
Buffalo, N.Y. 14214

The Research Foundation of State University of New York
P.O. Box 7126, Albany, N.Y. 12224

Engineering Evaluation
study of
ENVIRONMENTAL CONDITIONING SYSTEMS
for
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13. ABSTRACT

Several systems were reviewed including low temperature condensation and adsorption as well as the use of soda lime. The results indicate that low temperature condensation of CO_2 might be attractive for pressures up to 30 atmospheres. However, the large refrigeration requirement will probably preclude this technique at very high pressures. Adsorption systems seem to be very attractive but require careful design of the adsorbent bed at high pressures due to the low diffusivity of the gas.

Although the information is presented in a general way, the main purpose of this investigation was to select a system for the 170 atmosphere High Pressure Research Facility at the Department of Physiology - State University of New York at Buffalo. A combination low temperature dehumidification followed by low temperature adsorption of water then adsorption of carbon dioxide appears to be best suited for this application.

Data and references are included in the report to permit the reader to evaluate other design conditions.

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INTRODUCTION

A new high pressure research chamber has been provided by the office of Naval Research for the high pressure section of the Laboratory of Environmental Physiology in the Department of Physiology, State University of New York at Buffalo. This chamber has two compartments suitable for human occupancy and a working pressure of 170 atm abs, 2500 psig, or 5,600 ft. of equivalent sea water depth.

Except for experiments at relatively low pressures, utilizing compressed air for pressurization and ventilation, operation of such a chamber for human or animal studies requires an environmental conditioning system. Such a system must remove carbon dioxide and various gaseous contaminants, must provide for maintenance of the desired partial pressure of oxygen, and must ensure suitable temperature, humidity and circulation of the chamber atmosphere.

All of these requirements are important, but the means employed for removal of CO_2 is the central and most crucial component of most practical environmental control systems. Almost without exception, removal of CO_2 from high pressure research chambers has been accomplished by chemical adsorption utilizing soda lime or Baralyme R*. Although usually providing a satisfactory means of CO_2 removal, the use of a granular absorbent presents several problems. Most important is the fact that a relatively large volume of material must be replaced at quite frequent intervals.

In a chamber occupied by human subjects, pre-packed canisters of adsorbent can be passed in and out through an access lock and utilized in a basically simple and inexpensive internal scrubbing system. The main defect of this arrangement is that incapacitation of the occupants or malfunction of the lock or scrubber could cause a life-threatening crisis. An "external loop" system avoids such potential hazards and is also suitable for maintaining the chamber atmosphere during animal studies.

An external environmental control system must include at least one significant vessel, with working pressure equal to that at which the chamber will be used, to hold the adsorbent. This (or these) must be very readily opened for rapid replacement of the material. Other components of the environmental conditioning system may or may not be provided externally. In any case, the vessels and accompanying large-bore valves, piping and connections inevitably become items of major cost especially in a system of 2500 psig working pressure.

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*(indicates registered trademark)

In considering an environmental conditioning system for the new Buffalo chamber, we felt strongly that the usual approaches left much to be desired and that this warranted open-minded consideration of other possibilities. Our major objective was to develop, if possible, a system that combined the simple and inexpensive structures of an internal loop with total, or almost total, capability for operation and control from the outside of the chamber. In addition, we were intent upon providing a secondary system that could be put into operation from the outside in the event of failure of the primary system.

Our proposal for an engineering feasibility study of environmental control systems, which led to the present work, involved consideration of four concepts that had seldom or never been applied in high pressure research chambers. One of these concepts was the use of a compact countercurrent heat exchanger for dehumidification and temperature regulation. Two relatively uncommon approaches to CO_2 removal were included. One of these was use of low temperature in a multistage countercurrent heat exchange system. The other employed adsorption of CO_2 with synthetic zeolites and periodic in-situ regeneration of the adsorbent. The fourth concept employed familiar chemical CO_2 absorption but made use of the unusual pass-through lock design of the Buffalo Chamber for a system intended primarily for emergency use.

Although the primary motive of the study was to determine the most promising approaches to environmental conditioning for the new Buffalo chamber, we believe that this report will be useful in several other connections. We have made a particular effort to provide an instructive document applicable to many aspects of environmental conditioning in high pressure atmospheres.

I. Physiological Requirements

The design of a system to control the environmental parameters of a chamber must be predicated on certain assumptions for the rate of change of temperature and gas constituents. For short term operation, the major concern is the products of respiration from the chamber occupants. When using recirculation and purification systems, trace contaminants from outgassing of equipment, supplies and chamber occupants becomes more important as the time of exposure increases.

A. Oxygen, Carbon Dioxide and Water Rates:

The main use of the High Pressure Research Facility at the State University of New York at Buffalo is to investigate physiological effects under various conditions of pressure and gas composition. These experiments would typically have two or more chamber occupants alternating between performing exercise (as the experimental subject) and monitoring the test. A man might, for example, have a daily routine equivalent to six hours of relatively heavy work, ten hours of light work and eight hours of sleep. Table 1 is a compilation of the respiratory gas exchange of such a schedule, assuming a respiratory quotient (R.Q.) of 0.85. This is probably a reasonable approximation for an active diving schedule as well but would be conservative for an extended decompression period where the daily CO_2 production would only be about 2.2 #/day.

TABLE 1

	Metabolic Rate			$\dot{V}$ CO_2			$\dot{V}$ O_2	Respiratory H_2O	
Work	Kcal/ Min	BTU/ Hr.	Hours/ Day.	l/min STPD	#/hr.	#/day	l/min STPD	#/hr.	#/day
Heavy	7.5	1800	6	1.5	.38	2.3	1.75	.18	1.08
Light	2.5	600	10	.5	.13	1.3	0.6	.061	.61
Sleep	1	240	8	.25	.06	.5	.3	.023	.18
Daily Total/Man						4.1			1.87

In addition to respiratory water there will be evaporation from the skin assumed to be about .8 liter of water per day (1.8#) or a total water vapor from the chamber occupants of about 3.7 lbs/man day.

It will be necessary to replace the oxygen consumed by the chamber occupants. Based on the values in Table 1, this will amount to about 35 SCF/man during the daytime and 4 SCF/man when sleeping.

Obviously this idealized model will not be duplicated exactly. However, the values give realistic design parameters to determine daily totals and maximum instantaneous rates of CO_2 production. For comparison, the heavy work specified in Table I would correspond to a booted diver waking at maximum speed on a muddy bottom or swimming with fins at a speed of 90 feet per minute. The metabolic levels are obviously much higher than those for space activity where the estimated CO2 production is 2.1 to 2.3 #/man day and water production is .8 #/man day (Ref. 1, 2 and 3). There is some evidence that 4 lbs/man day is typical for long undersea exposure based on the experience in Tektite I (Ref. 4).

B. Chamber CO2 Equilibrium Pressure

1. Determine CO2 Loop flow given maximum CO2 pressure:

Figure I-1 shows the chamber equilibrium CO2 pressure versus flow rate through the CO_2 removal system for various work rates. This is valid for steady state conditions regardless of the vessel size. To find the required CO2 loop flow with a known maximum level of CO2 pressure enter the curve at the ordinate corresponding to the maximum CO2 level desired and draw a horizontal line. For each level of activity multiply the number of occupants at that work level times the required loop flow. Add the flows to determine the recirculation rate required.

Example 1: Determine the recirculation rate for a three man team with one man doing heavy work and two occupied at light duty. The maximum desired CO2 level is 4 mm Hg.

$$1 \times 10.7 + 2 \times 3.7 = 18 \text{ cfm}$$

This is shown on the horizontal dashed line on Fig. I-1.

2. Determine CO2 pressure for a known CO2 loop flow:

Since most circulation loops operate at a constant flow it is possible to use Fig. 1 to evaluate chamber CO2 pressures at varying conditions of occupant activity. This is done by entering the curve absissa at the loop flow and drawing a vertical line. Add the CO2 pressure contributed by each occupant.

Example 2: For the above case at 18 cfm flow, two men on light duty and one at heavy work the chamber equilibrium pressure would be:

$$1 \times 2.4 + 2 \times .8 = 4 \text{ mm Hg}$$

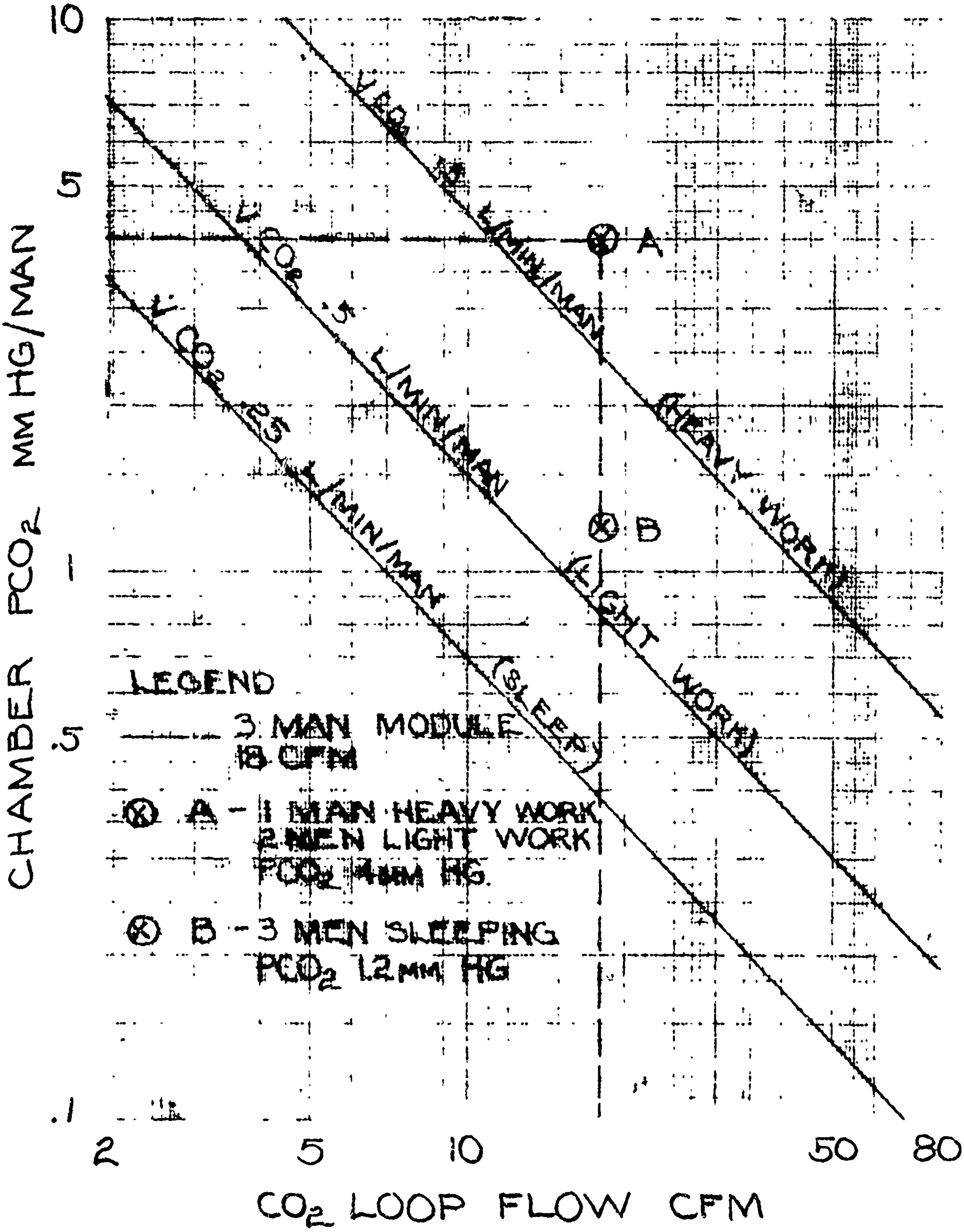

FIG. I-1

CHAMBER PCO_2 VS. CO_2 LOOP FLOW

When all three men are sleeping the CO_2 pressure would approach:

$$3 \times .39 = 1.2 \text{ mm Hg}$$

This is shown on the vertical dashed line on Fig. I-1

Note: The curves in Figure I-1 are based on complete removal of CO_2 in recirculation loop. While this is a valid assumption for most systems the rates and equilibrium pressures must be adjusted if only part of the CO_2 is removed by adding the exit pressure of CO_2 to the value given in Fig. I-1.

Figure I-2 has curves showing the increase in CO_2 level as a function of time, for the SUNYAB High Pressure Research Facility if the CO_2 removal system is out of service or not functioning properly. It is obvious that, especially in the smaller compartment, the CO_2 level will become prohibitively high in a short period of time, less than one hour with 3 men awake but not overly active (Curve B). It is certainly possible to have very high CO_2 production rates for short periods of time. In physiological measurements of maximum oxygen uptake, this could reach 4 liters of CO_2/minute for perhaps ten minutes. This gas would normally flow to measuring devices which would have separate CO_2 removal means. However, if the CO_2 was allowed to flow into the chamber this would be an excess of 2.5 liters (over the 1.5 l/min assumed for heavy work). The rate of CO_2 pressure increase would follow curve A in Fig. I-2 or after 10 minutes the pressure would increase by 4 mm Hg. This is not considered a problem.

The change (decrease) in oxygen partial pressure will be approximately the same as shown in Fig. I-2 for CO_2 (increase). Since the normal operating level for O_2 will be over 150 mm Hg, a uniform control of the oxygen makeup is much less critical than for CO_2 removal.

C. Humidity Control

Figure I-3 shows the amount of water removed per hour as a function of the flow through the water loop. There is some indication that a relative humidity of about 50% is desirable from the standpoint of diver comfort. However, there has been little study on the effect of varying the humidity at high pressures.

From Figure I-3 it can be seen that if an 18 cfm loop is used for a three man chamber, to maintain a low CO_2 level, the humidity level will drop well below 50%. As noted in part I-A the expected H_2O vapor production is 3.7 #/man day or about 11# total. Thus in an 18 cfm system the "average" R.H. will be about 25%. This can be remedied by periodically reversing the flow and evaporating the

TITLE: CO_2 Buildup - No CO_2 Loop Flow
SUNYAB High Pres Research Facility

BY: ______________ DATE: ______________

JOHN M. CANTY, P. E.
ENGINEERING CONSULTANT
117 CORNWALL AVENUE
TONAWANDA, NEW YORK 14150

(716) 832-6554

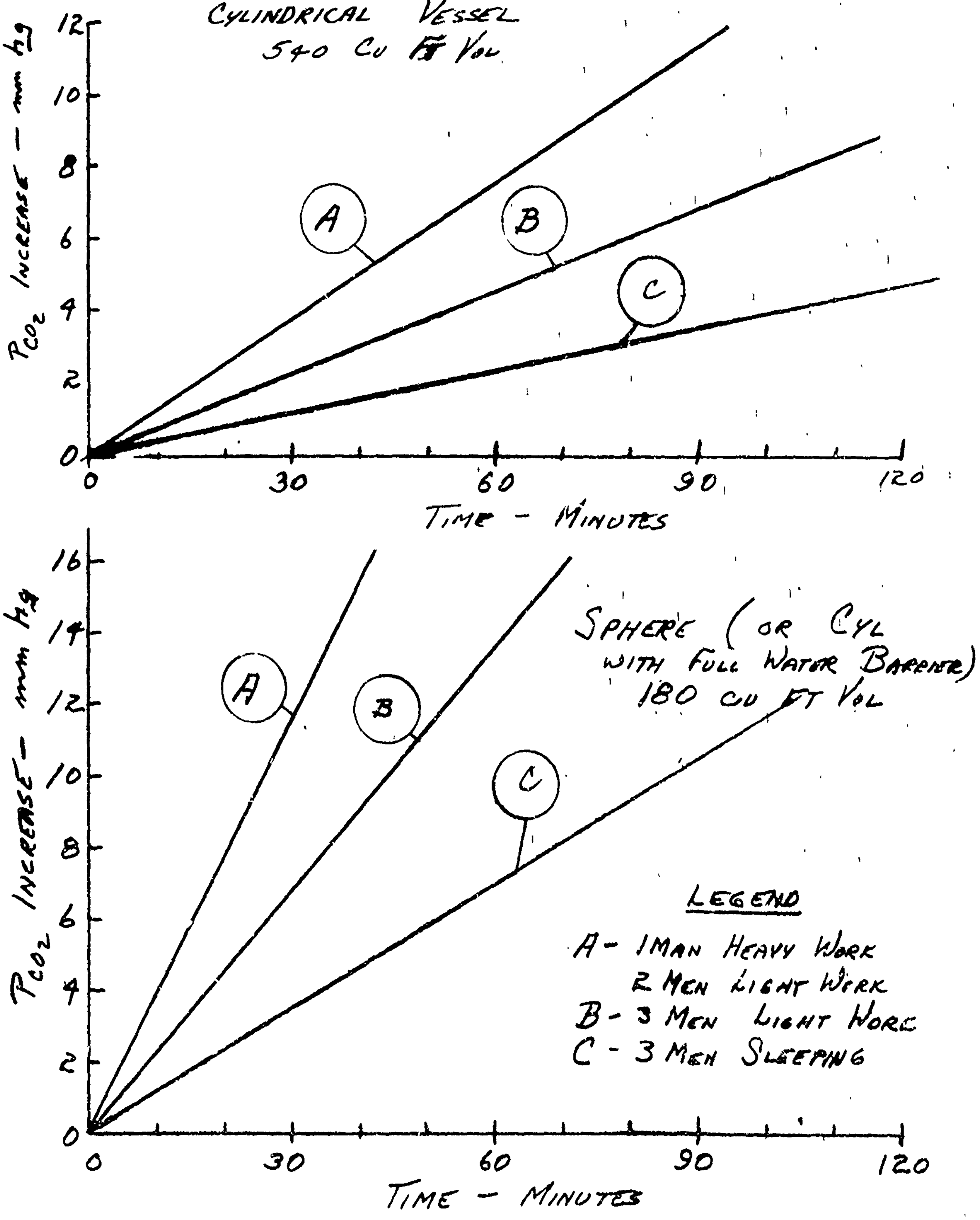

FIG I-2

TITLE: Moisture Removed in Water Loop f - Flow & Relative Humidity

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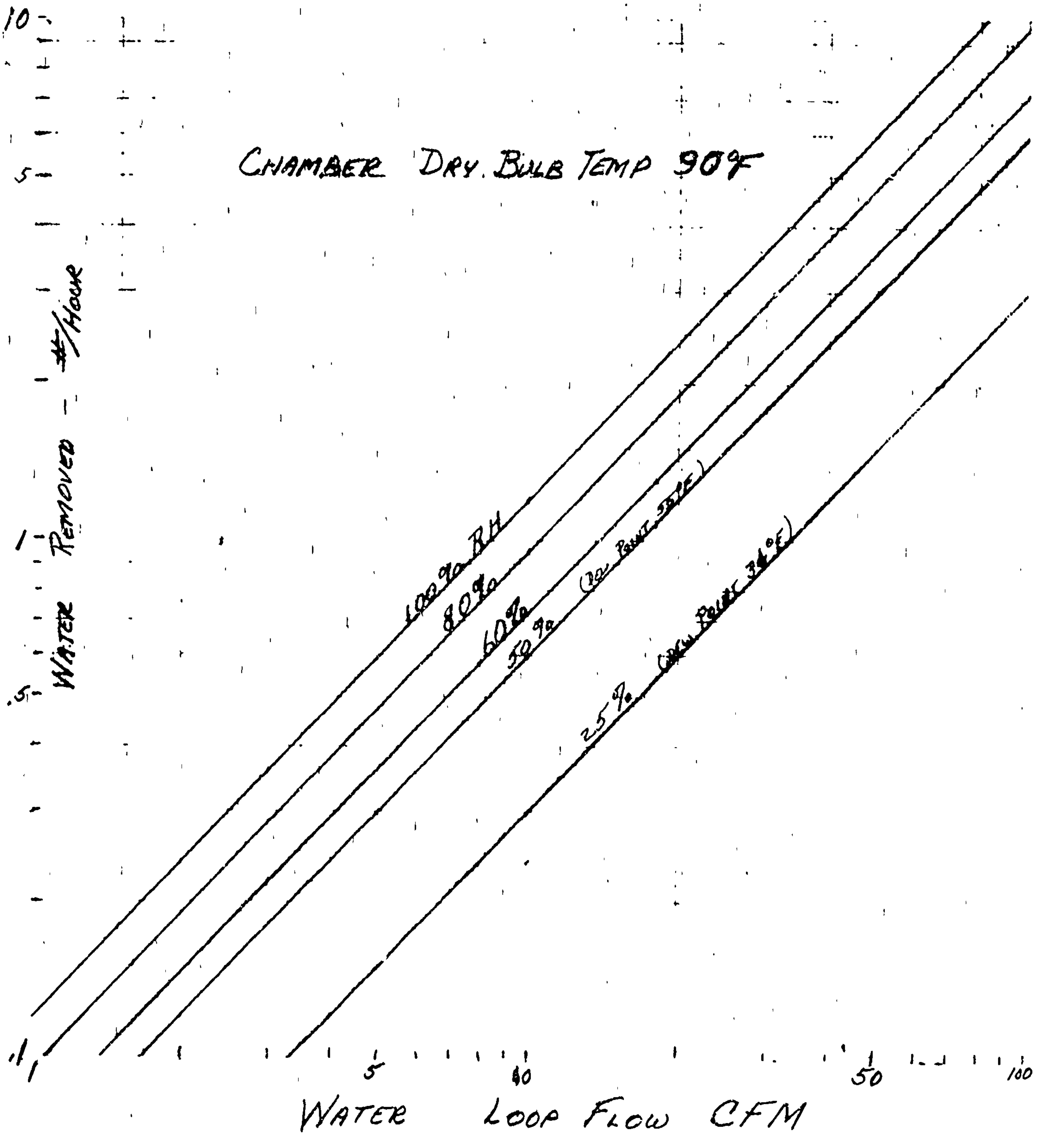
(716) 832-6554



condensed water, if a heat exchanger is used, or by humidfying the dry gas when it returned to the chamber atmosphere (similar to commercial air conditioning).

In view of the very high convective loss in helium atmospheres at high pressures (see Ref. 5), relative humidity is no doubt much less important at these pressures than it is at one atmosphere of air.

When the wet compartment of the High Pressure Facility is being used, it is expected that the relative humidity will approach 100% due to splashing and large wet surface areas in the chamber. In non-use periods, the water/gas interface will be covered to minimize evaporation.

D. Temperature:

It is well known that the ambient temperature in a helium environment must be higher than in air to maintain a suitable comfort level (Ref. 5). For the purpose of this study a chamber temperature of 90°F was chosen. At very high pressures the temperature will no doubt approach body temperature (98°F) to maintain comfort. However, the results shown in the following sections can be easily adjusted if a different ambient temperature is desired.

In view of the considerable amount of heat required due to heat loss from the vessel walls to the environment, only the process loop heat requirements are considered here. General heating will be accomplished by other means such as heating coils at the chamber floor.

E. Trace Contaminants:

It is difficult to obtain a quantative estimate of the type and amount of the various trace gases that will be present after prolonged exposure in a chamber. Several studies have been made (Ref. 6 and 7), however, the results for any particular chamber might be quite different, depending on the type of paint and other materials and equipment that might outgas.

Probably of greatest concern for manned occupancy is the CO level because of the physiological consequences. Again, except for some data in the Sea Lab II reports (see Ref. 8) little information is available.

Ammonia and methane might be of concern as well for animal experiments.

The control of CO will be through use of "hopcalite" in the dry side of the purification loop. In addition there is evidence that many of the trace contaminants will be removed by molecular sieves (Ref. 9).

Concentrated gas samples will be taken periodically to monitor the impurities. This will be done by passing some of the chamber gas through a liquid nitrogen trap. In this way all the gases with a freezing point above -320°F will be concentrated for analysis. If the concentration of impurities becomes too high, it will be necessary to have a complete chamber purge, passing the gas through a cleanup system. The proposed method of accomplishing the cleanup is by returning the purified gas to the chamber in a large flexible bag which will expand within the chamber. This will permit more efficient cleaning by a one pass method rather than by dilution.

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9. Personal communication G. D. Hopson - NASA Marshall Space Flight Center, Huntsville, Alabama.

II. Properties of Gases

A. Assumptions

It was assumed that the perfect gas laws apply in the analysis of methods for removing CO_2 and water. Although the gases deviate from the ideal state at high pressures, this assumption was made to permit a more complete analytic solution . The accuracy is considered sufficient for this study.

Thermal conductivity, specific heat and viscosity were assumed to be temperature dependent but invarient with pressure. While this would not be sufficiently accurate for oxygen, water or carbon dioxide alone, the assumption is considered justified because, at high pressures helium is the predominant gas. Helium has a very low critical temperature and critical pressure and for the pressure ranges considered this is a valid approximation (Ref. 1).

B. Density:

The gas density for the helium-oxygen mixture was determined from the perfect gas laws assuming the mixture was composed of one half atmosphere of oxygen with the balance helium. Helium density at 85°F and one atmosphere is .010 #/cu. ft. and oxygen is .081 #/cu. ft. The density of the mixture at 85°F would be

$$\rho_M = .01\,(P-.5) + .081\,(.5)$$

$$= .01P + .0355 \text{ \#/cu. ft.}$$

A curve of Density as a function of pressure is shown in Fig. II-1A.

C. Specific Heat:

The specific heat was determined by the weight % of each gas multiplied by the corresponding specific heat for that gas:

$$C_M = \frac{\rho_{o_2}}{\rho_M} C_{o_2} + \frac{\rho_{h_e}}{\rho_M} C_{h_e}$$

$$= \frac{.0355\,(.218)}{\rho_M} + \frac{.01\,P}{\rho_M}\,(1.25)$$

$$= \frac{1}{\rho_M}\,(.00776 + .0125P) \quad \text{BTU/\#}$$

This is shown in Fig. II-1B.

D. Viscosity and Thermal Conductivity:

The viscosity of oxygen is very close to that of helium over the temperature

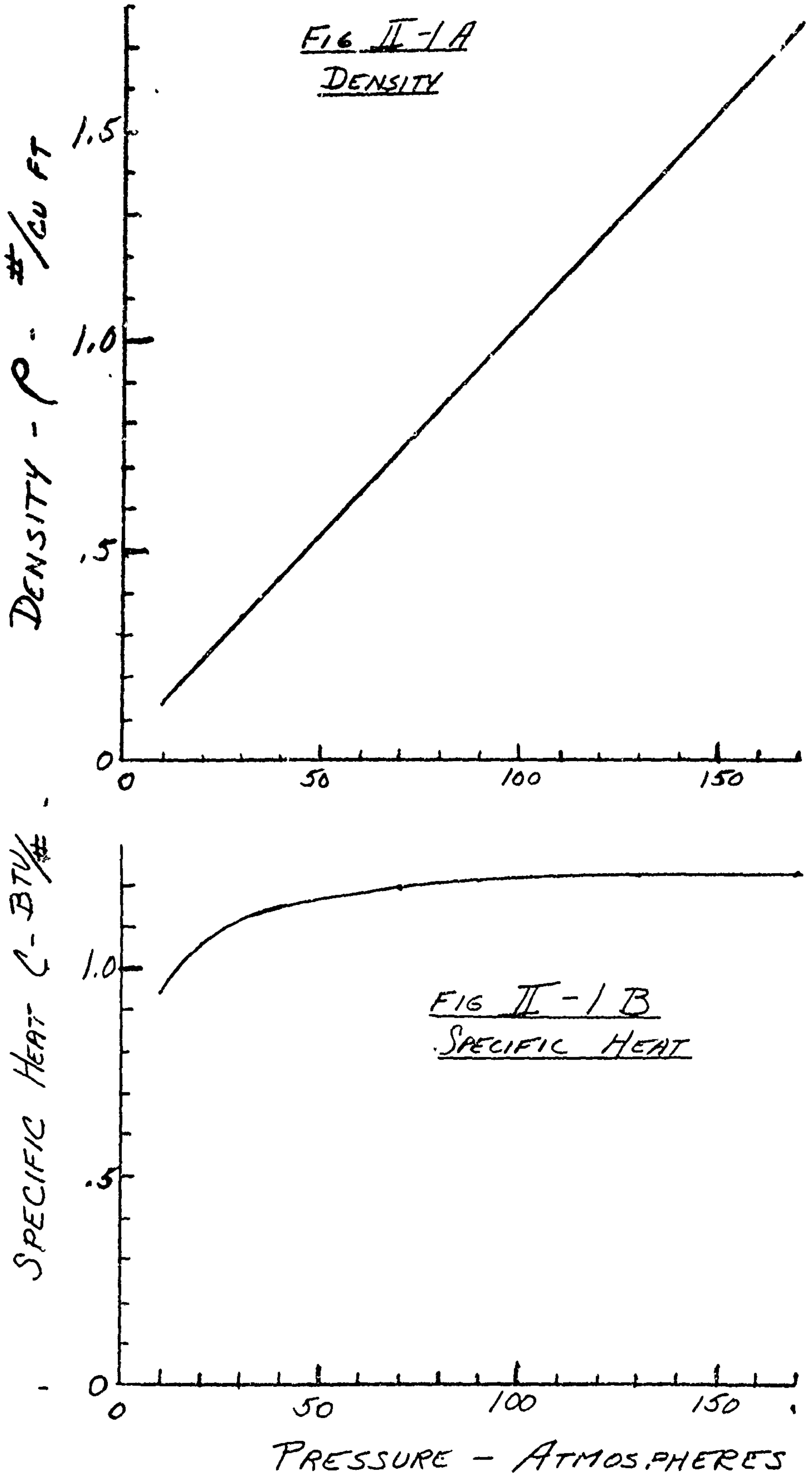

Fig II-1
Properties Helium + ½ ATA Oxygen

range of interest in this analysis. The viscosity value for helium was used (Reference 2) in the calculations.

The value for thermal conductivity was calculated on the basis that the Prandtl Number ($c\mu/k$) is essentially constant. For oxygen and helium gases the Prandtl No. has a value of approximately 0.7.

E. Diffusivity:

The diffusivity values for the gases were calculated using the relationship proposed by Wilke and Lee. For a more complete description and a tabular listing of constants for a number of gases the reader is referred to Reference 3 and 4 or to Reference 1, Section 14, pages 17 through 21.

Diffusivities for the gases of interest are given in Table II-1. Values for a background of air and of hydrogen are also given for reference purposes:

Table II-1
Diffusivity of Pairs of Gases
Cm^2/Sec @ 1 ATA

Gas	Helium			Hydrogen			Air		
	85°F	32°F	-190°F	85°F	32°F	-190°F	85°F	32°F	-190°F
Carbon Dioxide	.600	.504	.185	.616	.513	.178	.167	.139	.045
Water	.936	.779	.284	.894	.739	.246	.270	.225	.069
Oxygen	.744	.635	.237	.778	.694	.223	.225	.186	.063
Methane	.676	.572	.212	.682	.571	.200			

Diffusivity is inversely proportional to pressure, therefore at maximum chamber pressure the above values would be divided by 170. This is evident in the section on adsorption (Chapter IV) where, at high pressures, low diffusion of the gases reduces the adsorption efficiency appreciably. This will also pertain to removal of CO_2 by chemical means (hydroxides or peroxides). In view of this, special care should be used in the design of life support systems at high pressure to assure adequate contact time between the gas and adsorbent (or chemical).

F. Vapor Pressure of CO_2 and Water:

Figure II-2 is a curve of CO_2 vapor pressure vs. temperature. It is necessary to cool the gas to below -190°F in order to start freezing out CO_2 for the low partial pressures desired.

Figure II-3 shows the vapor pressure of water vs. temperature for the low temperature region. A second curve on this figure gives the weight of water in grains per cubic feet vs. temperature.

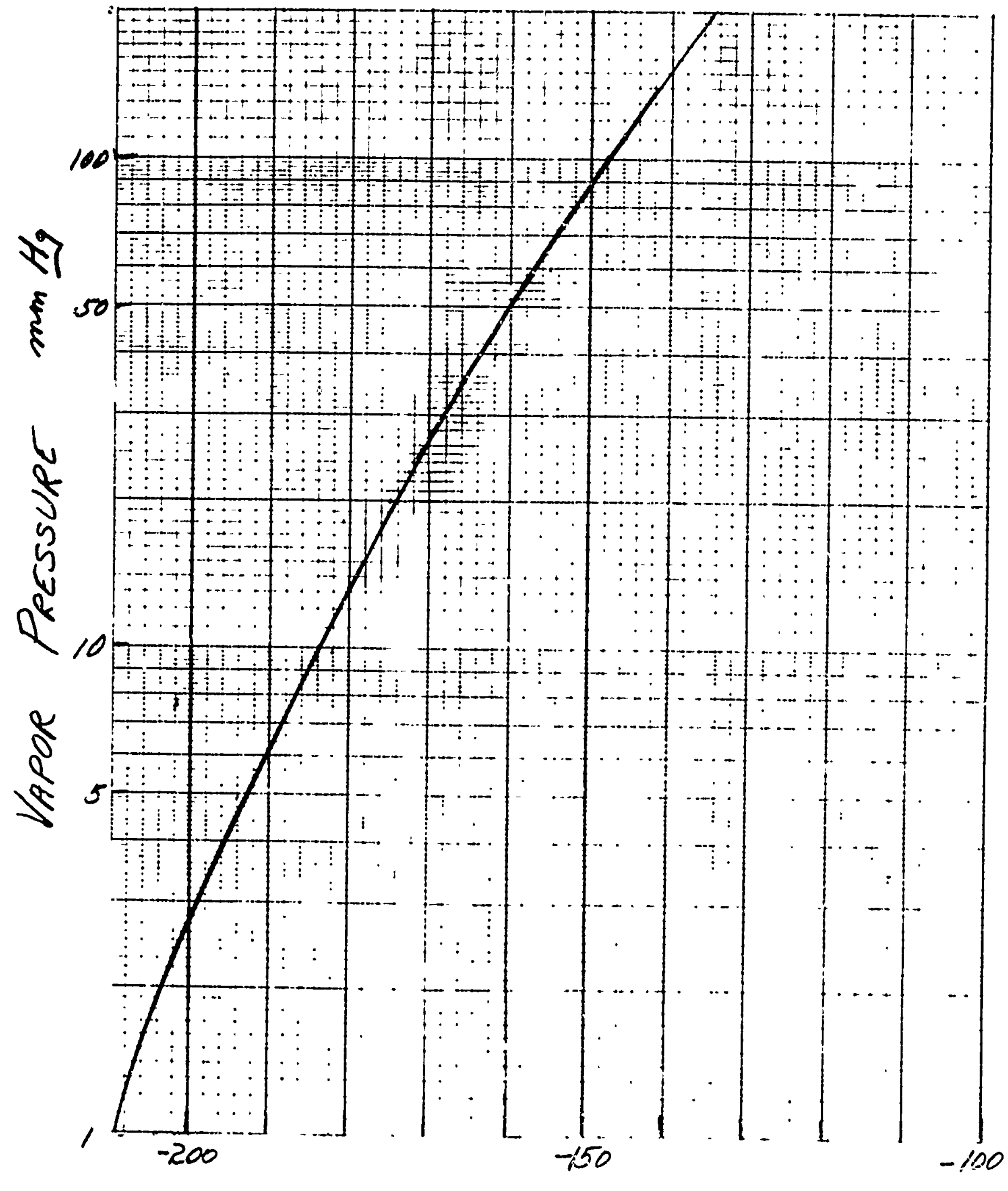

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FIG II - 2

VAPOR PRESSURE - CO_2

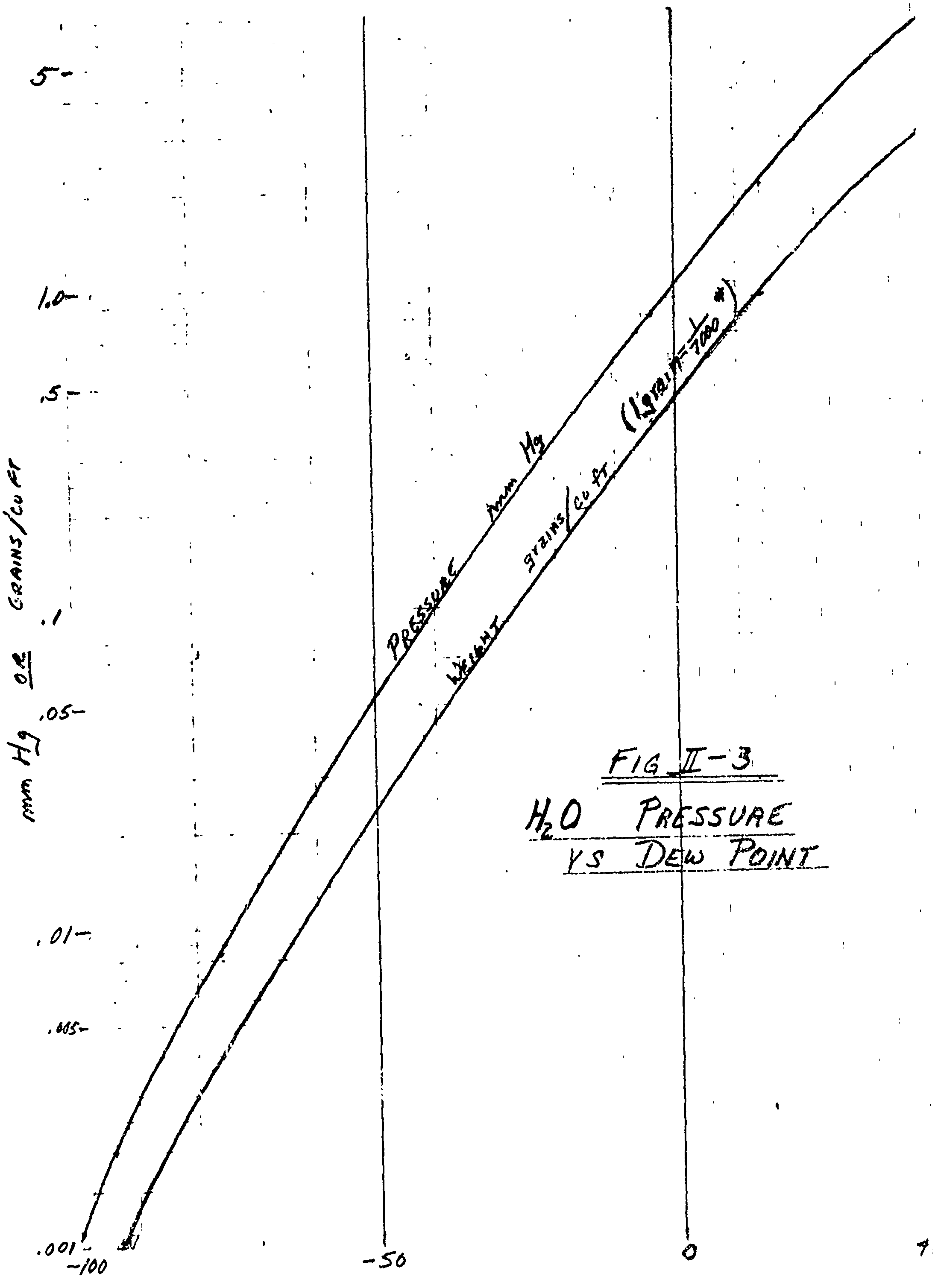

FIG II-3

H_2O PRESSURE VS DEW POINT

References:

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III. Heat Exchangers

A. General:

Helium, having the lowest boiling point of the elements, can be purified by lowering the temperature and condensing the unwanted contaminents. Most of the major impurities, water and CO_2, can be removed at temperatures about 100°F warmer than the normal boiling point of oxygen (297°F) and about 250°F warmer than the normal boiling point of helium (-452°F).

A counter-current heat exchanger is one in which the gas is cooled to the low temperature required in one passage and then returned to the same heat exchanger in an adjacent passage to be warmed by the incoming gas. These are used to make the process more efficient since it is necessary to only provide the refrigeration for a driving force (ΔT) across the heat exchanger and to make up for heat transfer from the warm ambient gas to the cold surfaces of the heat exchanger. This is shown schematically in Fig. III-1.

If material is removed (e.g. water and CO_2 condensed out of the gas stream) it is necessary to provide additional refrigeration to account for this in the system heat balance. In this case, however, with high pressure helium and a low percentage of contaminents the heat capacity of the gas requires the major part of the refrigeration and latent heat of the contaminents can be neglected as a first approximation.

B. Compact Heat Exchangers:

Heat transfer by convection can be estimated by the use of a coefficient (h)(Ref 1) in the simplified epression:

$$Q = h A \Delta t$$

Where:

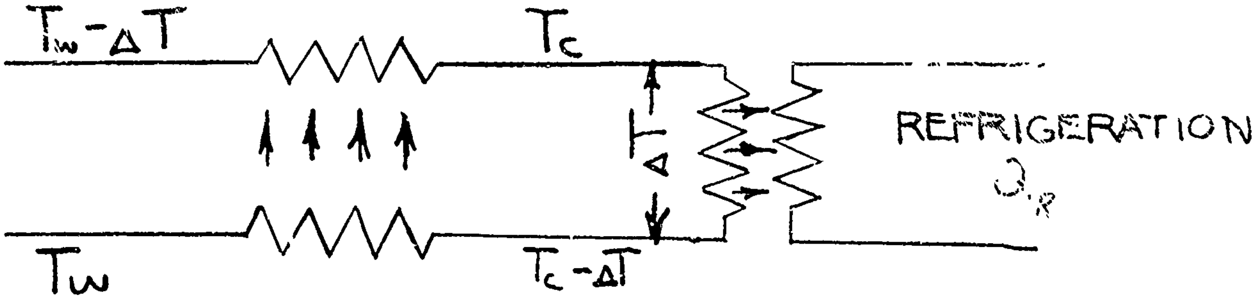
Q = heat transfer rate, BTU/hr.

h = overall coefficient, $BTU/Ft^2 Hr^oF$

A = Surface area, Ft^2

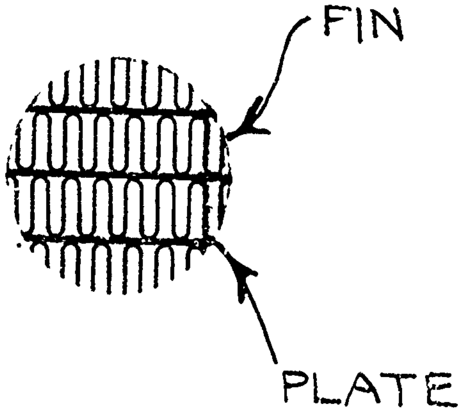
Δt = Temperature difference, °F

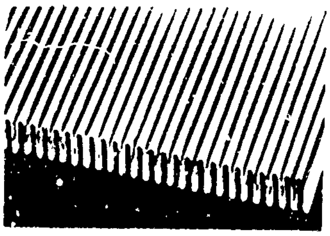
The quantity of heat can be increased by increasing the area, the film coefficient or the temperature difference. There are many styles of commercial heat exchangers which have very large surface area per unit of volume (Ref. 2). However, the brazed aluminum plate - fin type is probably the most efficient. These have alternate layers of corrugated aluminum passages separated by a flat sheet (Figure III-2) similar to many layers of corrugated cardboard. The very high thermal conductivity



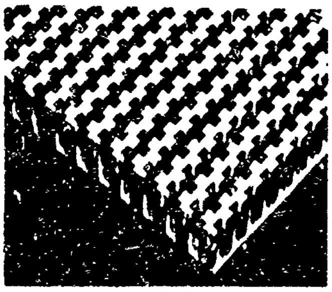
COUNTER CURRENT HEAT EXCHANGER

FIG III-1





STRAIGHT FIN



SERRATED FIN

FIG III-2

of aluminum assures that the temperature on the thin fin is essentially the same as the flat plate. Plate - fin heat exchangers of this type typically have surface areas of 350 to 500 sq. ft. per cubic foot of heat exchanger.

The film coefficient for gas can be increased appreciably by using a serrated fin (see Fig. III-2). The fin has notches, typically every 1/8 inch, along the flow. This interrupts the boundary layer and creates turbulence around the surface enhancing the heat transfer. This additional turbulence is accompanied by a higher pressure drop.

C. Heat Transfer and Pressure Drop:

Figure III-3-A shows the correlation between the heat transfer coefficient and the mass flow rate for two typical compact heat exchangers (see Ref. 2 for other exchangers). A curve showing the correlation between mass rate and friction factor is shown in Fig. III-3-B. Characteristic geometry dimensions of these two heat exchangers are given below:

Table III-1
Brazed Aluminum Heat Exchangers
(Ref 3)

		Fin				
Style	Fin Type	Height Inches	Thickness Inches	Spacing Fins/In.	Free Flow Area %	Heat Transfer Ft^2/Ft^3
A	Serrated(1/8")	.375	.006	15	88	410
B	Straight	.310	.006	12.5	90	365

Symbols used in Fig. III-3 and in the calculations are:

G = Mass velocity, lb/hr.ft.^{2}

c = Specific heat, BTU/#

h = Film coefficient, BTU/hr.ft^2 °F

k = Thermal conductivity, BTU/hr. ft.°F

ρ_1 = Entering density, lb/cu.ft.

ρ_2 = Exit density, lb./cu.ft.

μ = Viscosity, lb/ft.hr.

g = Gravity constant, 4.17×10^8 ft/hr^2

ΔP = Pressure drop, lb/ft.^{2}

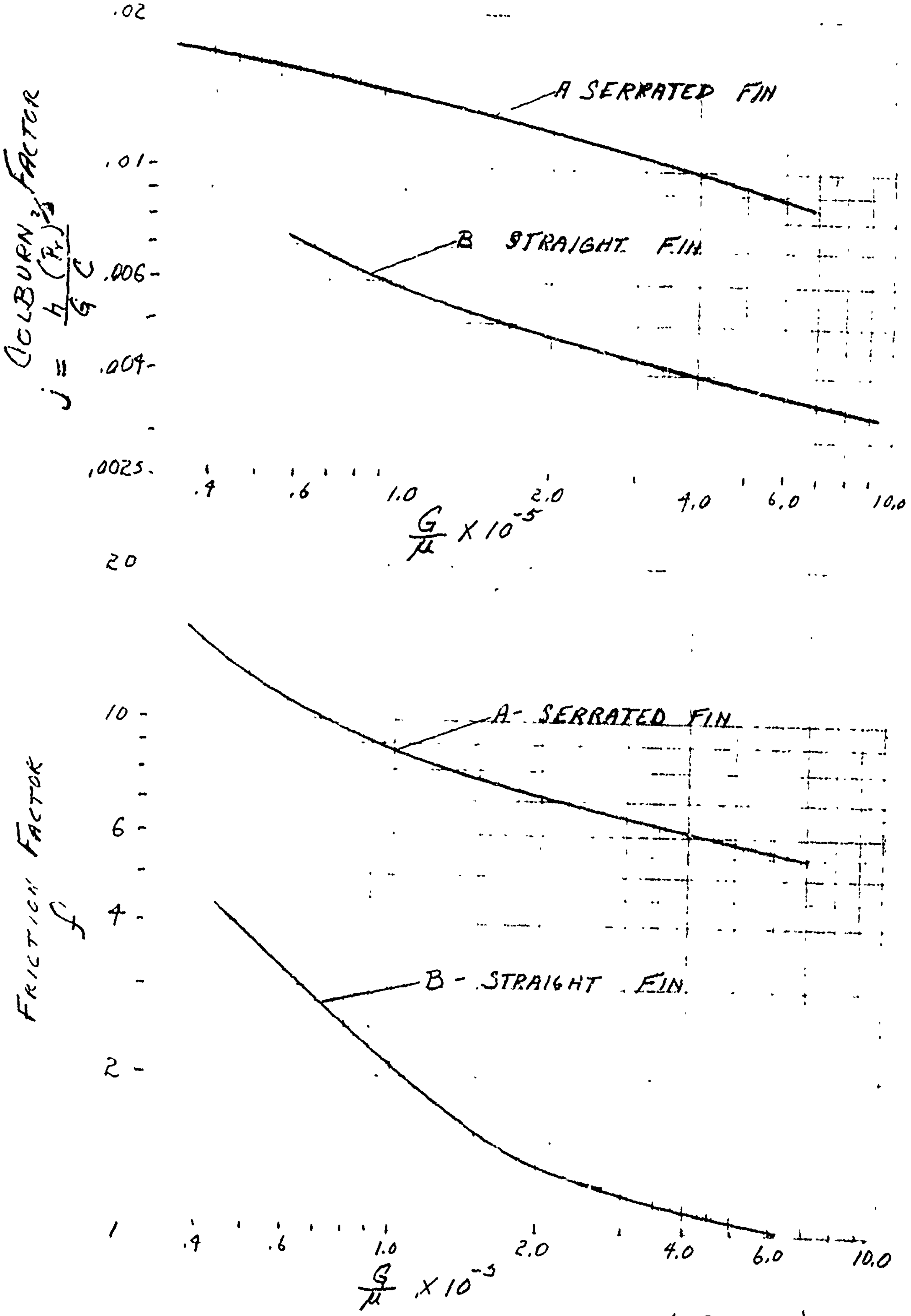


Fig III - 3 (Ref. 3)

Heat Transfer & Flow Friction

L = Heat exchanger length, ft.

f = Fanning friction factor, dimensionless

j = Colburn factor, dimensionless

Pr = Prandtl number, dimensionless = $C\mu/k$

The film coefficient can be determined by assuming a mass velocity and evaluating the gas properties for the average temperature. This will permit obtaining the Colburn factor (j) from curves on Fig. III-3-A. The film coefficient is the only unknown and can be calculated by:

$$h = j\ G\ C/(Pr)^{2/3}$$

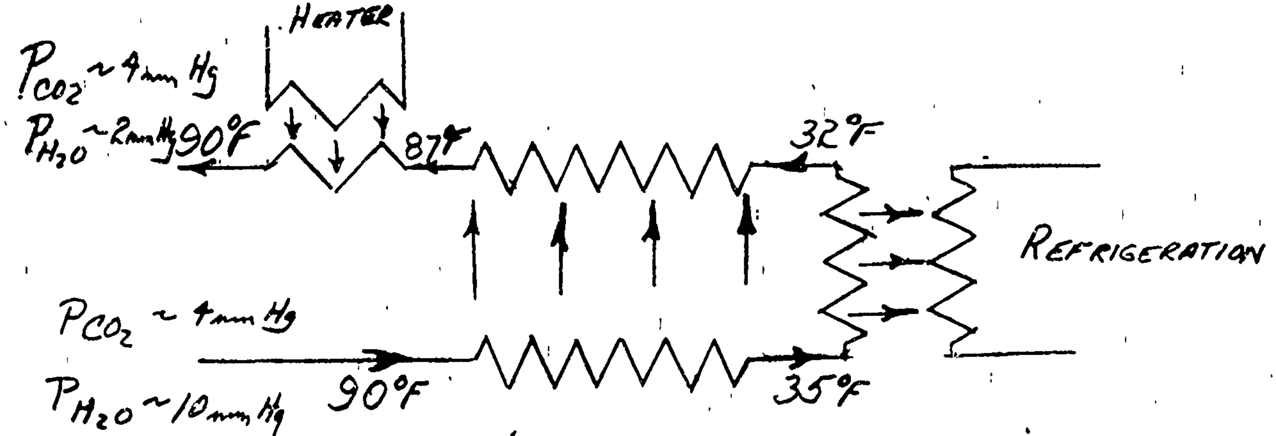
The friction factor f can be found from the curves in Figure III-3-B using the same mass velocity. The pressure drop per foot can be calculated from:

$$\Delta P = \frac{G^2}{2g}\left[\frac{8\ fL}{\rho_1 + \rho_2} - \frac{.364}{\rho_1} + \frac{1.507}{\rho_2}\right]$$

Heat exchanger length and total pressure drop curves for two fin styles are plotted on Figures III-4 and III-5. Figure III-5 is for low temperature (-190°F CO_2 removal) with a heat exchanger temperature difference (between passages) of 10°F. Figure III-4 is for a heat exchanger cooling to 30°F (dehumidification) with a temperature difference between passages of 3°F. In both cases the gas is Helium + 1/2 ATA oxygen with a chamber temperature of 90°F. The curves are plotted for a velocity of 2 ft/sec. Values for other gas velocities are tabulated in the computer print outs appended to this section.

References:

1. "Heat Transmission" W. McAdams, McGraw Hill Book Company.
2. "Compact Heat Exchangers" 2nd Edition, W. Kays and A. L. London, McGraw Hill Book Co.
3. "Brazed Aluminum Heat Transfer Surface" Engineering Bulletin, The Trane Co., LaCrosse, Wisconsin.



SCHEMATIC

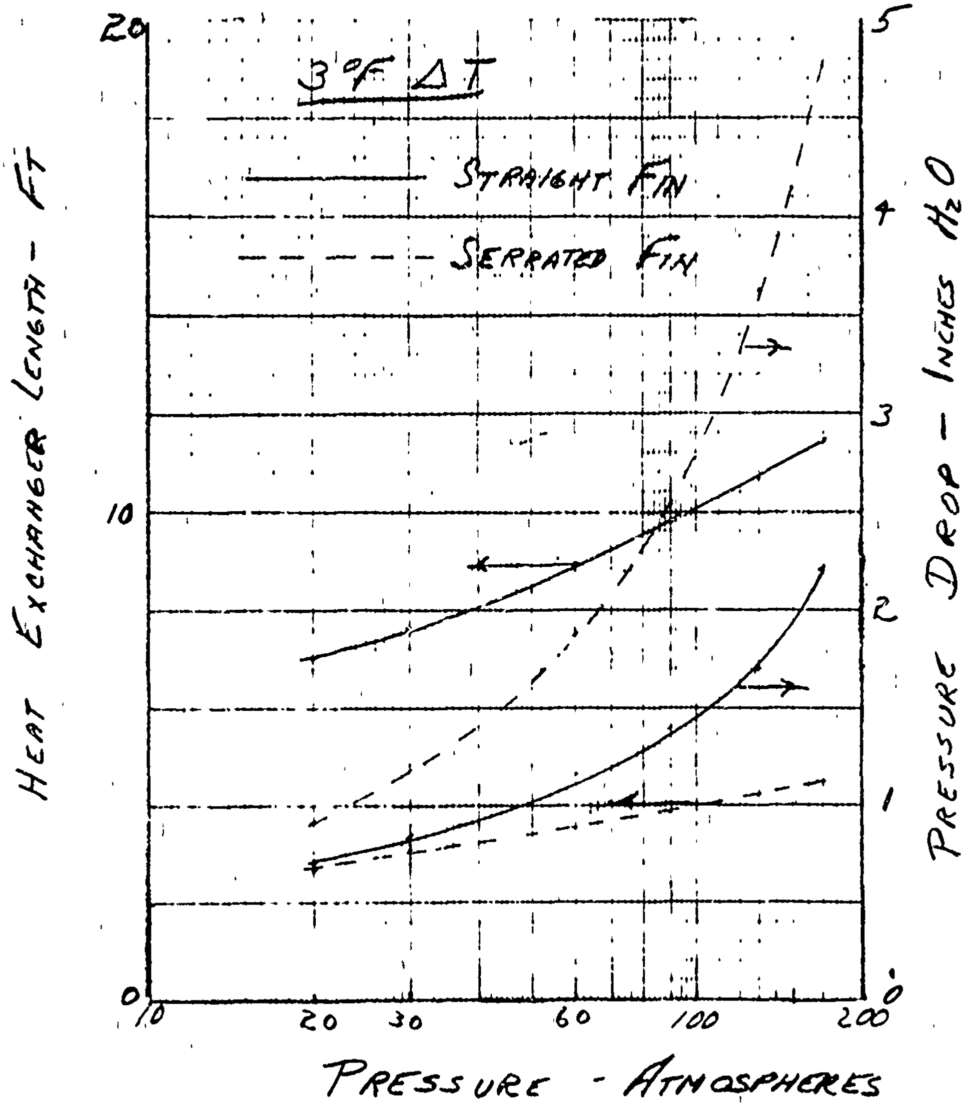
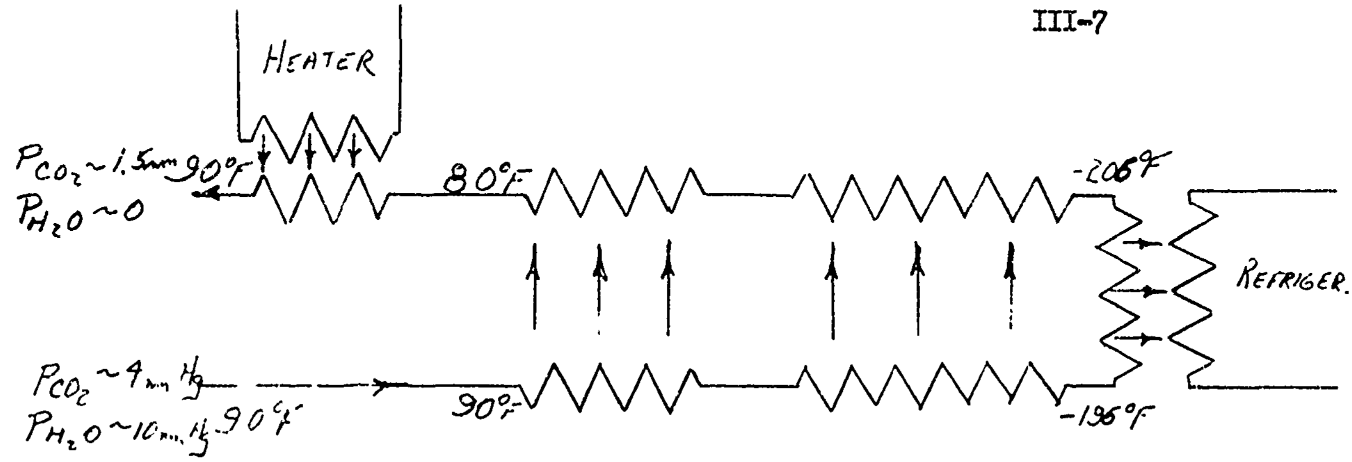


FIG III-4

LOW TEMPERATURE - DEHUMIDIFICATION



SCHEMATIC

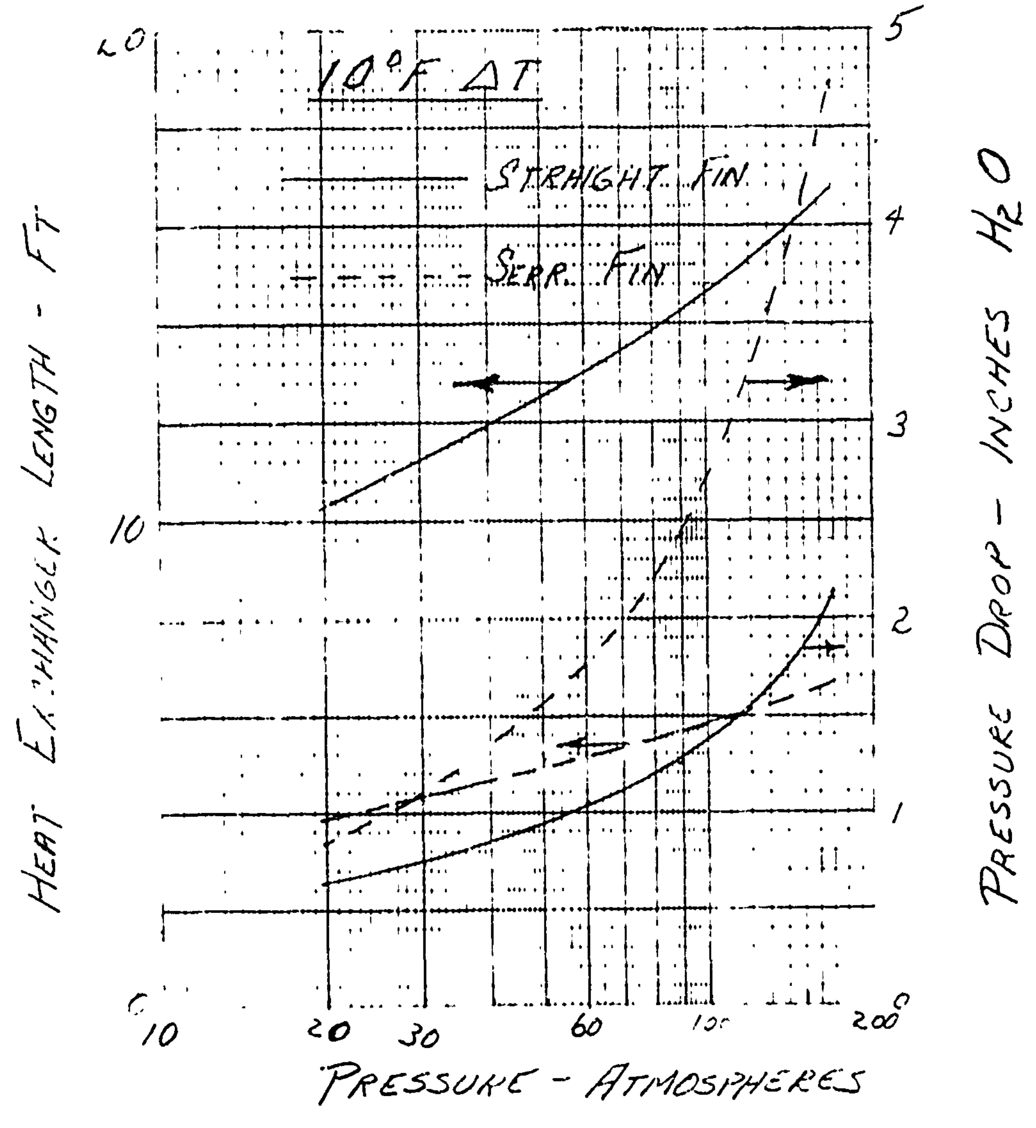


FIG III - 5

LOW TEMPERATURE - CO_2 REMOVAL

III-APPENDIX
Heat Exchanger Calculations

The following pages contain computer printouts for film coefficient h, length L, friction factor f and pressure drop for the two plate and fin heat exchangers described in Table III-1 and Figure III-3. These are arranged as follows (gas is helium + 1/2 ATA Oxygen):

Appendix III-A - Serrated Fin -cooling from 90°F to -190°F, 10°F temperature difference

Appendix III-B - Straight Fin-cooling from 90°F to -190°F, 10°F temperature difference

Appendix III-C - Serrated Fin - cooling from 90°F to 30°F, 3°F temperature difference

Appendix III-D - Straight Fin - cooling from 90°F to 30°F, 3°F temperature difference

To adjust the calculations for other temperature differences multiply the length and the pressure drop (for the desired velocity) by the ratio of t/10 for Appendices A & B and by t/3 for Appendices C & D.

```
  10    ATMOSPHERES

 DENSITY AT AMB. TEMP. IS            .135              LBS/CU FT
 HEAT CAPACITY IS                    .94777778         BTU/LB

 VELOCITY          FILM COEF           LENGTH          FRICT. FACT.     PRES. DROP
   FT/SEC          BTU/HR FT2 F       FEET                 F            INCHES H2O

  4                 31.407501         4.1408452        13.196832         1.8639262
  6                 42.569821         4.5825985        10.775168         3.7892076
  8                 52.82091          4.9243226        9.3315695         6.2684509
  10                62.443666         5.2068372        8.3464095         9.2624774
  12                71.59362          5.4496588        7.6191946         12.743019
  14                80.368232         5.6637752        7.3092069         17.292681
  16                88.833828         5.8560394        7.1451545         22.829208
  18                97.038208         6.0310388        7.003509          29.167062
  20                105.01731         6.1920078        6.8791839         36.313853
  22                112.79904         6.34132          6.7686205         44.276448
  24                120.40564         6.480773         6.6692364         53.061105
  26                127.8552          6.6117639        6.579101          62.67358
  28                135.16272         6.7354017        6.496735          73.1192
  30                142.34078         6.8525831        6.4209813         84.402988
  32                149.4001          6.9640438        6.3509183         96.529411
  34                156.34989         7.0703958        6.2858007         109.50302
  36                163.19816         7.1721543        6.2250178         123.32788
  38                169.95192         7.269757         6.1680631         138.00789
  40                176.61736         7.3635798        6.1145123         153.54677
```

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  30    ATMOSPHERES

 DENSITY AT AMB. TEMP. IS            .335              LBS/CU FT
 HEAT CAPACITY IS                    1.128209          BTU/LB

 VELOCITY          FILM COEF           LENGTH          FRICT. FACT.     PRES. DROP
   FT/SEC          BTU/HR FT2 F       FEET                 F            INCHES H2O

  2                 43.951853         4.3462741        11.847567         1.089543
  4                 73.917911         5.1686201        8.3774949         3.6641358
  6                 100.18856         5.7200184        7.233116          7.8770954
  8                 124.31461         6.1465598        6.8878843         14.330124
  10                146.96188         6.4991957        6.6314904         22.794567
  12                168.4964          6.8022866        6.4291022         33.306977
  14                189.14755         7.0695476        6.262812          45.897633
  16                209.07142         7.3095327        6.1222456         60.592442
  18                228.38053         7.5279676        6.0008783         77.414088
  20                247.15943         7.7288898        5.8943517         96.382767
  22                265.47382         7.9152618        5.7996166         117.5167
  24                283.37604         8.0893276        5.7144605         140.8325
  26                300.90867         8.252831         5.637229          166.34544
  28                318.10699         8.4071563        5.5666546         194.06966
  30                335.00064         8.5534226        5.5017459         224.01834
  32                351.61482         8.6925482        5.4417132         256.20379
```

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 60   ATMOSPHERES

DENSITY AT AMB. TEMP. IS          .635              LBS/CU FT
HEAT CAPACITY IS                  1.185748          BTU/LB

VELOCITY         FILM COEF          LENGTH           FRICT. FACT.      PRES. DROP
  FT/SEC         BTU/HR FT2 F       FEET                  F            INCHES H20

 2                 74.623694        5.0925755        8.6052742          1.7573552
 4                 125.50159        6.0561271        6.9509958          6.7521201
 6                 170.10524        6.7022063        6.4880101          15.693706
 8                 211.06768        7.2019894        6.1783418          28.550178
 10                249.51936        7.6151766        5.9483598          45.414004
 12                286.08177        7.9703114        5.7668203          66.358008
 14                321.14434        8.283464         5.6176601          91.442508
 16                354.97211        8.564657         5.4915739          120.71912


 90   ATMOSPHERES

DENSITY AT AMB. TEMP. IS:         .935              LBS/CU FT
HEAT CAPACITY IS:                 1.2063636         BTU/LB

VELOCITY         FILM COEF          LENGTH           FRICT. FACT.      PRES. DROP
  FT/SEC         BTU/HR FT2 F       FEET                  F            INCHES H20

 .5                35.079468        3.9648498        14.18325           .20757784
 1                 60.341832        4.7150276        10.029072          .69809498
 1.5               81.7875          5.2100358        8.1887033          1.4191489
 2                 101.48246        5.6071443        7.3224377          2.4241593
 2.5               119.97023        5.9288333        7.049868           3.8560514
 3                 137.54963        6.2053253        6.8347113          5.6343901
 3.5               154.4079         6.4491317        6.6579299          7.7642973
 4                 170.67247        6.668056         6.5084952          10.250156
 4.5               186.43518        6.8673213        6.3794709          13.095804
 5                 201.76507        7.0506108        6.2662236          16.304657
 5.5               216.71576        7.220627         6.1655117          19.879798
 6                 231.32998        7.379417         6.0749831          23.824038
 6.5               245.6425         7.5285715        5.9928791          28.18996
 7                 259.6821         7.6693534        5.9178523          32.829956
 7.5               273.47299        7.8027834        5.8488405          37.896255
 8                 287.03574        7.9296996        5.7850283          43.340942
 8.5               300.38807        8.0507987        5.7257129          49.16598
 9                 313.54535        8.1666673        5.670846           55.373221
 9.5               326.52106        8.277804         5.6184662          61.964418
 10                339.32705        8.3846365        5.569687           68.941239
 10.5              351.9739         8.4875347        5.5236812          76.30527
 11                364.47102        8.586821         5.48017            84.058029
 11.5              376.82687        8.682778         5.4389135          92.200966
```

130 ATMOSPHERES

DENSITY AT AMB. TEMP. IS: 1.335 LBS/CU FT
HEAT CAPACITY IS: 1.2194382 BTU/LB

VELOCITY FT/SEC	FILM COEF BTU/HR FT2 F	LENGTH FEET	FRICT. FACT. F	PRES. DROP INCHES H20
.5	47.37288	4.3327891	11.869733	.27103325
1	79.67197	5.1525836	8.8931685	.91148526
1.5	107.98681	5.7022712	7.2377142	1.9570765
2	133.99074	6.1274891	6.8922631	3.5603416
2.5	158.40077	6.4790309	6.6357061	5.6633458
3	181.61145	6.7811814	6.4331893	8.275171
3.5	203.87	7.0476132	6.2667934	11.40334
4	225.34467	7.2868537	6.1261376	15.054289
4.5	246.15671	7.5046109	6.0046931	19.233654
5	266.39728	7.7049097	5.8980988	23.946453
5.5	286.13719	7.8907035	5.8033036	29.197218
6	305.43284	8.0642292	5.7180932	34.990062
6.5	324.33014	8.2272253	5.6408126	41.328794
7	342.8671	8.3810718	5.5701935	48.216922
7.5	361.07568	8.5268842	5.5052435	55.657719
8	378.98304	8.6655782	5.4451726	63.654249

170 ATMOSPHERES

DENSITY AT AMB. TEMP. IS: 1.735 LBS/CU FT
HEAT CAPACITY IS: 1.2264841 BTU/LB

VELOCITY FT/SEC	FILM COEF BTU/HR FT2 F	LENGTH FEET	FRICT. FACT. F	PRES. DROP INCHES H20
.5	57.995673	4.6254606	10.411944	.32903144
1	97.536708	5.5006306	7.4163096	1.1173487
1.5	132.20155	6.0874485	6.9223306	2.5970157
2	164.03654	6.5413891	6.5919325	4.7245256
2.5	193.92022	6.9166768	6.346555	7.5151811
3	222.33561	7.239237	6.1528629	10.981033
3.5	249.58537	7.5236657	5.9937177	15.132064
4	275.87547	7.7790664	5.8591909	19.976815
4.5	301.35436	8.0115327	5.7430384	25.522764
5	326.13364	8.2253613	5.641089	31.776571
5.5	350.29998	8.4237051	5.5504244	38.744242
6	373.92244	8.6089522	5.4689271	46.431255

Appendix III-B
90°F-190°F
10°ΔT
Straight Fin

10 ATMOSPHERES

½ ATM. v_2

DENSITY AT AMB. TEMP. IS .135 LBS/CU FT
HEAT CAPACITY IS .94777778 BTU/LB

VELOCITY FT/SEC	FILM COEF BTU/HR FT2 F	LENGTH FEET	FRICT. FACT. F	PRES. DROP INCHES H2O
4	13.75511	10.505478	3.7795969	1.3539112
6	18.643717	11.626222	2.788541	2.486629
8	23.133245	12.493189	2.2473617	3.8275532
10	27.347591	13.209939	1.9010366	5.3481062
12	31.35487	13.825986	1.6580764	7.0290059
14	35.197766	14.369207	1.4770474	8.8560971
16	38.905326	14.856989	1.3211451	10.695515
18	42.498485	15.300969	1.2828102	13.536512
20	45.992982	15.709353	1.2494619	16.711743
22	49.401039	16.088164	1.2200422	20.221209
24	52.732396	16.441961	1.1937894	24.06491
26	55.994979	16.77429	1.1701383	28.242846
28	59.195351	17.087964	1.1486587	32.755016
30	62.339026	17.385257	1.1290163	37.601422
32	65.430699	17.668037	1.1109462	42.782062
34	68.474404	17.937856	1.0942355	48.296937
36	71.473648	18.196021	1.0787105	54.146047
38	74.4315	18.443643	1.0642279	60.329392
40	77.350668	18.681675	1.0506681	66.846972

30 ATMOSPHERES

DENSITY AT AMB. TEMP. IS .335 LBS/CU FT
HEAT CAPACITY IS 1.128209 BTU/LB

VELOCITY FT/SEC	FILM COEF BTU/HR FT2 F	LENGTH FEET	FRICT. FACT. F	PRES. DROP INCHES H2O
2	19.248987	11.026658	3.2150275	.74980195
4	32.372808	13.112981	1.9116668	2.1195903
6	43.878201	14.511899	1.3451322	3.7117385
8	54.444356	15.59405	1.2517865	6.5986463
10	64.362866	16.4887	1.1838666	10.310385
12	73.794043	17.257653	1.1311168	14.846954
14	82.838342	17.935704	1.0883555	20.208354
16	91.564127	18.544555	1.0526228	26.394585
18	100.02067	19.098733	1.0220794	33.405647
20	108.24501	19.60848	.99550918	41.241539
22	116.26591	20.081312	.97206901	49.902263
24	124.10629	20.522924	.95115207	59.387817
26	131.78482	20.937738	.93230805	69.698201
28	139.31693	21.329267	.9151942	80.833417
30	146.71561	21.70035	.89954409	92.793464
32	153.99189	22.053317	.88514674	105.57834

60 ATMOSPHERES

DENSITY AT AMB. TEMP. IS .635 LBS/CU FT
HEAT CAPACITY IS 1.185748 BTU/LB

VELOCITY FT/SEC	FILM COEF BTU/HR FT2 F	LENGTH FEET	FRICT. FACT. F	PRES. DROP INCHES H2O
2	32.68191	12.920053	1.9901601	1.0303388
4	54.964202	15.364619	1.2686901	3.1225574
6	74.498644	17.003746	1.1463909	7.0257541
8	92.4384	18.271714	1.0668369	12.49023
10	109.27855	19.319985	1.0089521	19.515984
12	125.29129	20.220975	.96399599	28.103017
14	140.64716	21.015455	.92755257	38.251328
16	155.46224	21.728852	.89709935	49.960918

90 ATMOSPHERES

DENSITY AT AMB. TEMP. IS: .935 LBS/CU FT
HEAT CAPACITY IS: 1.2063636 BTU/LB

VELOCITY FT/SEC	FILM COEF BTU/HR FT2 F	LENGTH FEET	FRICT. FACT. F	PRES. DROP INCHES H2O
.5	15.713635	10.058971	4.0111878	.15632097
1	26.427079	11.9622	2.5039871	.44193838
1.5	35.819343	13.23835	1.6474115	.81160497
2	44.444873	14.225533	1.4888796	1.2491742
2.5	52.541707	15.04167	1.295317	1.7951578
3	60.240714	15.74314	1.2376013	2.5850273
3.5	67.623899	16.361686	1.1908143	3.5185094
4	74.747068	16.917105	1.1517178	4.5956041
4.5	81.650445	17.422648	1.118299	5.8163114
5	88.364266	17.887661	1.0892274	7.1806313
5.5	94.912014	18.318998	1.0635806	8.6805639
6	101.3124	18.721854	1.0406945	10.440109
6.5	107.58066	19.100265	1.0200765	12.135267
7	113.72939	19.457434	1.0013515	14.074037
7.5	119.76919	19.795851	.98422808	16.15642
8	125.70908	20.117942	.96847535	18.382416
8.5	131.55682	20.425175	.95390766	20.752025
9	137.31913	20.719137	.94037363	23.265246
9.5	143.00192	21.001095	.9277488	25.922079
10	148.61039	21.272133	.91592744	28.722525
10.5	154.14915	21.53319	.90482323	31.666584
11	159.62234	21.785083	.89436109	34.754256
11.5	165.03367	22.028529	.88447713	37.98554

130 ATMOSPHERES

DENSITY AT AMB. TEMP. IS: 1.335 LBS/CU FT
HEAT CAPACITY IS: 1.2194382 BTU/LB

VELOCITY FT/SEC	FILM COEF BTU/HR FT2 F	LENGTH FEET	FRICT. FACT. F	PRES. DROP INCHES H20
.5	20.747247	10.992446	3.2240543	.18669426
1	34.892571	13.072296	1.9170342	.52775971
1.5	47.293496	14.466873	1.3463899	.92246073
2	58.682076	15.545667	1.252957	1.6399302
2.5	69.372601	16.437541	1.1849735	2.5623909
3	79.537862	17.204108	1.1321744	3.6898429
3.5	89.286131	17.880056	1.0893731	5.0222862
4	98.691094	18.487018	1.053607	6.5597297
4.5	107.80586	19.039476	1.0230351	8.3021465
5	116.67034	19.547641	.99644	10.249564
5.5	125.31556	20.019007	.97297791	12.401972
6	133.76621	20.459248	.95204142	14.759372
6.5	142.0424	20.872775	.93317977	17.321763
7	150.16077	21.26309	.91604993	20.089145
7.5	158.13533	21.633021	.90038518	23.061518
8	165.97797	21.984893	.88597437	26.238883

170 ATMOSPHERES

DENSITY AT AMB. TEMP. IS: 1.735 LBS/CU FT
HEAT CAPACITY IS: 1.2264841 BTU/LB

VELOCITY FT/SEC	FILM COEF BTU/HR FT2 F	LENGTH FEET	FRICT. FACT. F	PRES. DROP INCHES H20
.5	25.399565	11.734965	2.6487361	.2127609
1	42.716806	13.955304	1.5749479	.60140002
1.5	57.898488	15.444082	1.2610035	1.1986677
2	71.840818	16.595746	1.173496	2.1309649
2.5	84.928564	17.547865	1.109824	3.3296386
3	97.373261	18.366212	1.0603733	4.7946709
3.5	109.30746	19.087819	1.0202864	6.5260799
4	120.82137	19.73578	.98678855	8.5238594
4.5	131.98001	20.325555	.95815545	10.78801
5	142.82225	20.868046	.93324699	13.31853
5.5	153.41605	21.371252	.91127284	16.115422
6	163.76165	21.84123	.89166411	19.178684

Appendix III-C
1/2 O_2-Bal He
90°F-30°F
Serrated Fin

10 ATMOSPHERES

DENSITY AT AMB. TEMP. IS: .135 LBS/CU FT
HEAT CAPACITY IS: .94777778 BTU/LB

VELOCITY FT/SEC	FILM COEF BTU/HR FT2 F	LENGTH FEET	FRICT. FACT. F	PRES. DROP INCHES H20
4	32.699631	2.9273725	14.305025	2.0518197
6	44.321178	3.2396702	11.680004	4.1729093
8	54.994005	3.4012522	10.11518	6.9054189
10	65.012648	3.600976	9.0472923	10.206388
12	74.539039	3.8526389	8.2590101	14.04482
14	83.674646	4.0040086	7.6463576	18.59674
16	92.488523	4.1399299	7.343753	23.861558
18	101.03044	4.2636458	7.1981705	30.484502
20	109.33781	4.3774429	7.0703898	37.952437
22	117.43968	4.4829992	6.9567533	46.272011
24	125.35922	4.5815856	6.8546068	55.451202
26	133.11527	4.6741896	6.7619661	65.494522
28	140.72342	4.7615955	6.6773108	76.408083
30	148.19679	4.8444369	6.5994515	88.196803
32	155.54653	4.9232341	6.5274411	100.86573
34	162.78225	4.9984197	6.4605135	114.4194
36	169.91227	5.0703579	6.3980412	128.86203
38	176.94388	5.1393582	6.3395035	144.1977
40	183.88354	5.2056862	6.2844642	160.43027

30 ATMOSPHERES

DENSITY AT AMB. TEMP. IS: .395 LBS/CU FT
HEAT CAPACITY IS: 1.128209 BTU/LB

VELOCITY FT/SEC	FILM COEF BTU/HR FT2 F	LENGTH FEET	FRICT. FACT. F	PRES. DROP INCHES H20
2	45.760067	3.0127141	12.842457	1.1763532
4	76.958953	3.5827411	9.0809881	3.9592137
6	104.3104	3.9649547	7.4341594	8.0739849
8	129.42902	4.2606212	7.079332	14.686503
10	153.00801	4.5050584	6.8158116	23.359256
12	175.42840	4.7151524	6.6077902	34.129513
14	196.92923	4.9004102	6.436886	47.028141
16	217.67279	5.066761	6.2924125	62.081551
18	237.77620	5.2181739	6.1676718	79.312867
20	257.32777	5.3574475	6.0581843	98.742679
22	276.39563	5.4866353	5.9608161	120.38956
24	295.03435	5.6072928	5.873293	144.27045
26	313.28829	5.7206287	5.7939149	170.40092
28	331.19417	5.8276026	5.721379	198.79537
30	348.78283	5.9289902	5.6546661	229.46725
32	366.08054	6.0254282	5.5929648	262.42911
34	383.10987	6.1174461	5.5356187	297.69279
36	399.89045	6.2054895	5.4820899	335.26944
38	416.43944	6.2899374	5.4319326	375.16963

```
 60  ATMOSPHERES

DENSITY AT AMB. TEMP. IS:          .635           LBS/CU FT
HEAT CAPACITY IS: .                1.185748       BTU/LB

VELOCITY          FILM COEF        LENGTH         FRICT. FACT.    PRES. DROP
 FT/SEC           BTU/HR FT2 F     FEET                F          INCHES H2O

 2                 77.693773       3.5120189       9.3278949       1.8891143
 4                130.66483        4.1765179       7.1441977       6.8850916
 6                175.1035         4.6220768       6.6683433      16.00003
 8                219.75117        4.9667448       6.3500679      29.10401
 10               259.78479        5.2516932       6.1136935      46.290817
 12               297.8514         5.4966066       5.9271082      67.63431
 14               334.35648        5.7125677       5.7738022      93.195667
 16               369.57595        5.9064882       5.6442113     123.02724
 18               403.70869        6.0829952       5.5323206     157.17485
 20               436.90419        6.2453509       5.4341117     195.67933


 90  ATMOSPHERES

DENSITY AT AMB. TEMP. IS:          .935           LBS/CU FT
HEAT CAPACITY IS:                  1.2063636      BTU/LB

VELOCITY          FILM COEF        LENGTH         FRICT. FACT.    PRES. DROP
 FT/SEC           BTU/HR FT2 F     FEET                F          INCHES H2O

 .5                37.355578       2.7295924      15.374277        .22251544
 1                 62.824343       3.2460507      10.871255        .74887694
 1.5               85.152303       3.5923456       8.8763429       1.5281274
 2                105.65753        3.8602265       7.6871384       2.5206205
 2.5              124.9059         4.0816926       7.245818        3.9253998
 3                143.20853        4.2720429       7.0246811       5.7352718
 3.5              160.76037        4.439891        6.8429861       7.9027983
 4                177.69408        4.5906089       6.6898978      10.432417
 4.5              194.10528        4.7277927       6.5567872      13.028813
 5                210.06585        4.8539779       6.4403923      16.593046
 5.5              225.63163        4.9710252       6.3368812      20.250637
 6                240.84708        5.0803438       6.2438363      24.243682
 6.5              255.74843        5.1830289       6.1594583      28.634645
 7                270.36563        5.2799499       6.0823881      33.4061
 7.5              284.72389        5.3718096       6.0114164      38.560252
 8                298.84462        5.4591847       5.9458223      44.099214
 8.5              312.74628        5.5425552       5.8848593      50.024972
 9                326.44486        5.6223247       5.8279524      56.339401
 9.5              339.95439        5.6988365       5.7746306      63.044278
 10               353.28724        5.7723851       5.7244956      70.141888
 10.5             366.45439        5.8432251       5.6772111      77.632041
 11               379.46565        5.9115786       5.6324905      85.518071
 11.5             392.32983        5.97764         5.5900873      93.800847
 12               405.0549         6.041581        5.5497882     102.48178
 12.5             417.64806        6.1035541       5.5114075     111.56282
 13               430.11587        6.1636949       5.4747823     121.04347
 13.5             442.46435        6.2221251       5.4397693     130.9268
```

Appendix III-C
1/2 O_2 Bal He
90°F-30°F
Serrated Fin

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130  ATMOSPHERES

DENSITY AT AMB. TEMP. IS:        1.335         LBS/CU FT
HEAT CAPACITY IS:                1.2194382     BTU/LB

VELOCITY         FILM COEF         LENGTH         FRICT. FACT.     PRES. DROP
  FT/SEC         BTU/HR FT2 F      FEET               F            INCHES H20

 .5                49.321839       2.9797247      12.866484         .29033357
 1                 82.949115       3.5435098      9.0979778         .97717176
 1.5               112.42948       3.9215382      7.4388854         1.990299
 2                 139.50323       4.2139671      7.0838325         3.6203292
 2.5               164.91751       4.4557277      6.8201446         5.7582213
 3                 189.08309       4.6635212      6.6119988         8.4131605
 3.5               212.25737       4.8467503      6.440978          11.592755
 4                 234.61553       5.0112796      6.2964127         15.303516
 4.5               256.28379       5.1610345      6.1715927         19.551143
 5                 277.35708       5.2987831      6.0620356         24.34071
 5.5               297.9091        5.4265563      5.9646055         29.676798
 6                 317.99859       5.5458925      5.8770268         35.563581
 6.5               337.67334       5.6579874      5.7975982         42.004895
 7                 356.97293       5.76379        5.7250161         49.004295
 7.5               375.93062       5.8640674      5.6582609         56.565091
 8                 394.57471       5.9594494      5.5965203         64.690381
 8.5               412.92954       6.0504597      5.5391377         73.383079
 9                 431.01624       6.137539       5.485575          82.645936
 9.5               448.85334       6.2210621      5.4353857         92.481559


170  ATMOSPHERES

DENSITY AT AMB. TEMP. IS:        1.735         LBS/CU FT
HEAT CAPACITY IS:                1.2264841     BTU/LB

VELOCITY         FILM COEF         LENGTH         FRICT. FACT.     PRES. DROP
  FT/SEC         BTU/HR FT2 F      FEET               F            INCHES H20

 .5                60.381662       3.179202       11.286279         .35322099
 1                 101.54945       3.7007296      7.9806041         1.1888817
 1.5               137.64042       4.18406[illegible]  7.1147357    2.6393179
 2                 170.78513       4.4960[illegible]   6.7751542    4.800896
 2.5               201.89825       4.754[illegible]    6.5229565    7.6359527
 3                 231.48268       [illegible]    6.3238808         11.15667
 3.5               259.85351       [illegible]    6.1603121         15.373137
 4                 287.22521       5.3467591      6.0220463         20.29399
 4.5               313.75232       5.5065394      5.9026653         25.926786
 5                 339.55104       5.6535095      5.7978822         32.270257
 5.5               364.7116        5.7898364      5.7046976         39.354476
 6                 389.30591       5.9171617      5.6209351         47.160978
 6.5               413.39248       6.0367607      5.5449676         55.702850
 7                 437.01977       6.1496462      5.4755484         64.984814
 7.5               460.2285        6.2566367      5.411702          75.01125
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III-18

Appendix III-D
Straight Fin
90°F to 30°F
1/2 O_2 bal Hel

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 10  ATMOSPHERES

DENSITY AT AMB. TEMP. IS:          .135            LBS/CU FT
HEAT CAPACITY IS:                  .94777778       BTU/LB

VELOCITY        FILM COEF           LENGTH          FRICT. FACT.     PRES. DROP
  FT/SEC        BTU/HR FT2 F       FEET                 F            INCHES H2O

  4               14.321006        7.4268524        4.2655386         1.5537231
  6               19.410735        8.2191633        3.147063          2.8569326
  8               24.084966        8.8320658        2.5363044         4.4018595
 10               28.472693        9.3387725        2.1454523         6.1558784
 12               32.644835        9.7742875        1.8712548         8.0969762
 14               36.64583        10.158318         1.666951         10.208993
 16               40.505922       10.503155         1.5080956        12.479406
 18               44.246907       10.817027         1.335586         14.416601
 20               47.88517        11.105735         1.3008658        17.798273
 22               51.433437       11.373535         1.2702357        21.535911
 24               54.901849       11.623652         1.2429029        25.629514
 26               58.298657       11.858592         1.2182787        30.079082
 28               61.630695       12.080344         1.1959155        34.884616
 30               64.903704       12.290516         1.1754649        40.046115
 32               68.12257        12.490427         1.1566514        45.56358
 34               71.291496       12.681176         1.1392592        51.43781
 36               74.414131       12.863686         1.1230895        57.666406
 38               77.493672       13.038742         1.1080111        64.251767
 40               80.532936       13.207019         1.0938934        71.193094

 30  ATMOSPHERES

DENSITY AT AMB. TEMP. IS:          .335            LBS/CU FT
HEAT CAPACITY IS:                  1.128209        BTU/LB

VELOCITY        FILM COEF           LENGTH          FRICT. FACT.     PRES. DROP
  FT/SEC        BTU/HR FT2 F       FEET                 F            INCHES H2O

  2               20.040905        7.6433673        3.6283828          .84428773
  4               33.704651        9.0895467        2.1574493         2.3925145
  6               45.683385       10.059237         1.5917401         4.4016847
  8               56.68424        10.809354         1.3[illegible]3286         6.8923145
 10               67.010806       11.4295           1.2325718        10.769241
 12               76.82999        11.962516         1.1776519        15.507708
 14               86.246378       12.432522         1.1331313        21.107713
 16               95.331149       12.85456          1.0959285        27.569258
 18              104.1356         13.2387           1.0641286        34.892342
 20              112.69829        13.592043         1.0364652        43.076966
 22              121.04918        13.919797         1.0120607        52.123128
 24              129.21213        14.225909          .99028323       62.03083
 26              137.20655        14.513447          .97066395       72.800072
 28              145.04854        14.784844          .95284603       84.430853
 30              152.7516         15.042068          .93655206       96.923173
 32              160.32724        15.286735          .92156239      110.27703
 34              167.78535        15.520187          .90770036      124.49243
 36              175.1345         15.743557          .89482191      139.56987
 38              182.38224        15.957804          .88280816      155.50785
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60 ATMOSPHERES

DENSITY AT AMB. TEMP. IS: .635 LBS/CU FT
HEAT CAPACITY IS: 1.185748 BTU/LB

VELOCITY FT/SEC	FILM COEF BTU/HR FT2 F	LENGTH FEET	FRICT. FACT. F	PRES. DROP INCHES H20
2	34.02647	8.9101221	2.2463344	1.15607
4	57.225473	10.595981	1.320885	3.2450852
6	77.563578	11.72638	1.1905543	7.3014416
8	96.24139	12.600815	1.1107275	12.980341
10	113.77436	13.32374	1.0504612	20.281782
12	130.44587	13.945095	1.0036556	29.205767
14	146.43349	14.492996	.96571282	39.752293
16	161.85808	14.984979	.93400674	51.921363
18	176.80672	15.432784	.90690517	65.712975
20	191.3449	15.844687	.88332904	81.127129

90 ATMOSPHERES

DENSITY AT AMB. TEMP. IS: .935 LBS/CU FT
HEAT CAPACITY IS: 1.2063636 BTU/LB

VELOCITY FT/SEC	FILM COEF BTU/HR FT2 F	LENGTH FEET	FRICT. FACT. F	PRES. DROP INCHES H20
.5	16.360107	6.9250769	4.7526189	.17465679
1	27.514311	8.2353508	2.8259241	.4947904
1.5	37.292979	9.1109138	2.0849327	.91009658
2	46.273371	9.7935377	1.6803045	1.4026242
2.5	54.703315	10.355405	1.3486074	1.8624262
3	62.719065	10.838331	1.2885172	2.6818938
3.5	70.406	11.264168	1.2398054	3.6503554
4	77.822223	11.646545	1.1991004	4.7678111
4.5	85.00961	11.994585	1.1643067	6.034261
5	91.999643	12.314722	1.1340391	7.4497049
5.5	98.81677	12.611675	1.1073371	9.0141429
6	105.48047	12.88902	1.0835095	10.727575
6.5	112.00661	13.149536	1.0620432	12.590001
7	118.40831	13.395429	1.0425479	14.601422
7.5	124.69659	13.62848	1.02472	16.761836
8	130.88086	13.850154	1.0083192	19.071244
8.5	136.96917	14.061668	.99315219	21.529647
9	142.96855	14.264046	.97906135	24.137044
9.5	148.88514	14.458159	.96591661	26.893435
10	154.72434	14.644755	.95360943	29.79882
10.5	160.49097	14.824479	.94204039	32.850199
11	166.18934	14.997894	.93115582	36.056572
11.5	171.82329	15.165494	.92086523	39.408939
12	177.39631	15.327715	.91111925	42.9103
12.5	182.91156	15.484943	.90186811	46.560656
13	188.37191	15.637522	.89306835	50.360005
13.5	193.78001	15.785762	.8846818	54.308349

130 ATMOSPHERES

DENSITY AT AMB. TEMP. IS: 1.335 LBS/CU FT
HEAT CAPACITY IS: 1.2194382 BTU/LB

VELOCITY FT/SEC	FILM COEF BTU/HR FT2 F	LENGTH FEET	FRICT. FACT. F	PRES. DROP INCHES H2O
.5	21.600805	7.5596719	3.6385701	.2085735
1	36.328079	8.9900156	2.1635067	.59105778
1.5	49.239188	9.9490877	1.5962092	1.0874253
2	61.096303	10.690991	1.3045046	1.6995931
2.5	72.226645	11.304346	1.2337243	2.6556141
3	82.810113	11.831526	1.178753	3.8240844
3.5	92.959434	12.296385	1.1341908	5.2050037
4	102.75133	12.713802	1.0969533	6.7983722
4.5	112.24108	13.093736	1.0651236	8.6041898
5	121.47025	13.443209	1.0374343	10.622457
5.5	130.47114	13.767374	1.013007	12.853172
6	139.26945	14.070135	.99120916	15.296337
6.5	147.88613	14.354524	.97157158	17.951952
7	156.33851	14.622949	.95373696	20.820015
7.5	164.64115	14.877356	.93742775	23.900527
8	172.80644	15.119344	.92242406	27.193489
8.5	180.84505	15.35024	.90854907	30.6989
9	188.76624	15.571164	.89565859	34.416759
9.5	196.5781	15.783065	.8836336	38.347068

170 ATMOSPHERES

DENSITY AT AMB. TEMP. IS: 1.735 LBS/CU FT
HEAT CAPACITY IS: 1.2264841 BTU/LB

VELOCITY FT/SEC	FILM COEF BTU/HR FT2 F	LENGTH FEET	FRICT. FACT. F	PRES. DROP INCHES H2O
.5	26.444523	8.0657532	2.9892834	.23775881
1	44.47421	9.5918511	1.7774385	.67394273
1.5	60.280478	10.615128	1.3128822	1.2415835
2	74.796407	11.406698	1.2217775	2.2072596
2.5	88.422593	12.061114	1.155483	3.4488431
3	101.37928	12.623586	1.1039979	4.9663341
3.5	113.80446	13.119565	1.0622618	6.7597325
4	125.79206	13.564926	1.0273858	8.8290384
4.5	137.40977	13.970294	.99757473	11.174252
5	148.70848	14.343163	.97164152	13.795372
5.5	159.72771	14.689029	.94876334	16.692401
6	170.49894	15.012058	.92834789	19.865336
6.5	181.0478	15.315486	.90995566	23.314179
7	191.39552	15.60188	.89325212	27.03893
7.5	201.55993	15.873319	.87797723	31.039588

IV. Adsorption

A. General:

The use of an adsorbent to remove CO_2 and/or water is attractive in that it permits a self-contained system that can be regenerated from outside of the vessel if required.

Adsorbents have been used to remove CO_2 from the atmosphere in several applications. Great Britain and France both have programs to develop molecular sieve systems for submarines. In addition several systems have been designed for space use. At least one of these uses an adiabatic desorption cycle (see Ref. 1 and 2). In a space application, the convenience of a readily available high vacuum simplifies the equipment needed for reactivation.

B. Moisture Removal:

Many adsorbents are used to dry gases. Among the more popular are silica gel, activated alumina and molecular sieve. Each of these has properties which make it desirable for certain purposes. Silica gel can be reactivated at a relatively low temperature. Activated alumina has somewhat greater capacity but requires a higher reactivation temperature. Type 13X Molecular Sieve will produce an extremely dry gas. This material (Type 13X MS) will adsorb about 25% water by weight and maintain a very low partial pressure of water (See Fig. IV-1 and Ref. 3). The dimensionless plot shown in Fig. IV-2 indicates the relatively high adsorption potential for water at 77°F. The 400°F curve is included for the reactivation cycle.

Figure IV-3 is a plot of the isotherm curves for silica gel as taken from Ref. 4. These are plotted in dimensionless form in Fig. IV-4. Comparing the shape of the curves in Fig. IV-3 and Fig. IV-1 it is obvious that molecular sieve will have a higher capacity for water, at low partial pressures, than will silica gel. Conversely, it is much easier to remove the water from silica gel.

C. CO_2 Removal:

Either Type 5A Molecular Sieve or Type 4A could be used for the removal of CO_2. Type 5A has a slightly greater capacity. The isotherms of 5A Sieve are shown in Fig. IV-5. A dimensionless plot of the CO_2 isotherms for 5A Molecular Sieve is shown in Figure IV-6. There is a significant increase in the amount of CO_2 that can be adsorbed at 32°F over that at 77°F as shown in IV-5. In addition the adsorption efficienty is enhanced (smaller R in IV-6) resulting in a sharper "break-through" curve.

Comparison of Figs. IV-2 and IV-6 shows that molecular sieves have a much stronger adsorption potential for water than for CO_2. (5A

Molecular Sieve water isotherms are similar to 13X.) For this reason it is necessary to remove essentially all of the water prior to adsorbing CO_2. Otherwise the water will displace the CO_2.

Referring to Fig. IV-4, water vapor can be removed by reducing the gas temperature or by an adsorbent or by a combination of low temperature and adsorption.

D. Reactivation:

There are two possible cycles to consider in designing an adsorption bed of this type. An adiabatic desorption by lowering the pressure is practical if a source of low pressure is readily available. In this case the quantity of adsorbed material would follow the isotherm to the new equilibrium pressure. It is necessary to have a relatively high vacuum to remove much water if the adsorbent is at ambient temperature. In the case of CO_2, an adiabatic desorption is possible by either lowering the adsorbent pressure or by purging with a gas having a low partial pressure of CO_2.

The other cycle for desorption is to raise the temperature. This is the more common approach. In the case of water adsorbed on molecular sieve it is necessary to increase the temperature to over 400°F before reactivation is very effective. Carbon dioxide can be removed at 212°F with reasonable efficiency.

E. Dimensionless Isotherm Plots:

The dimensionless plots of adsorption isotherms (Fig. IV-2, 4, 6) are useful in determining the adsorption efficiency. The curves in Fig. IV-2 were obtained from the data in IV-1 by dividing the partial pressure of water at a given adsorbent loading by the partial pressure when no more moisture will be adsorbed or $\frac{c}{Co}$. The ordinate for the curve is the concentration ratio $\frac{q}{Q}$ or weight percent (at the corresponding water partial pressure) divided by the maximum weight percent, when no more water will be adsorbed.

The shape of the isotherm curve as plotted above will given an indication of the ease with which the adsorbent can remove water (or CO_2). The shape of the curve determines the "R" factor (see Ref. 5 for a more detailed review of the mechanism of adsorption). For ideal adsorption, the isotherm would be a horizontal line on Fig. IV-1 and IV-2. In other words, the adsorbent would have maximum capacity regardless of the concentration of water vapor in the gas. This would give an "R factor" of zero.

A curve with an "R factor" greater than 1 will result in unfavorable adsorption. It is desirable to have a small R during the adsorption part of the cycle and large R during the desorption phase.

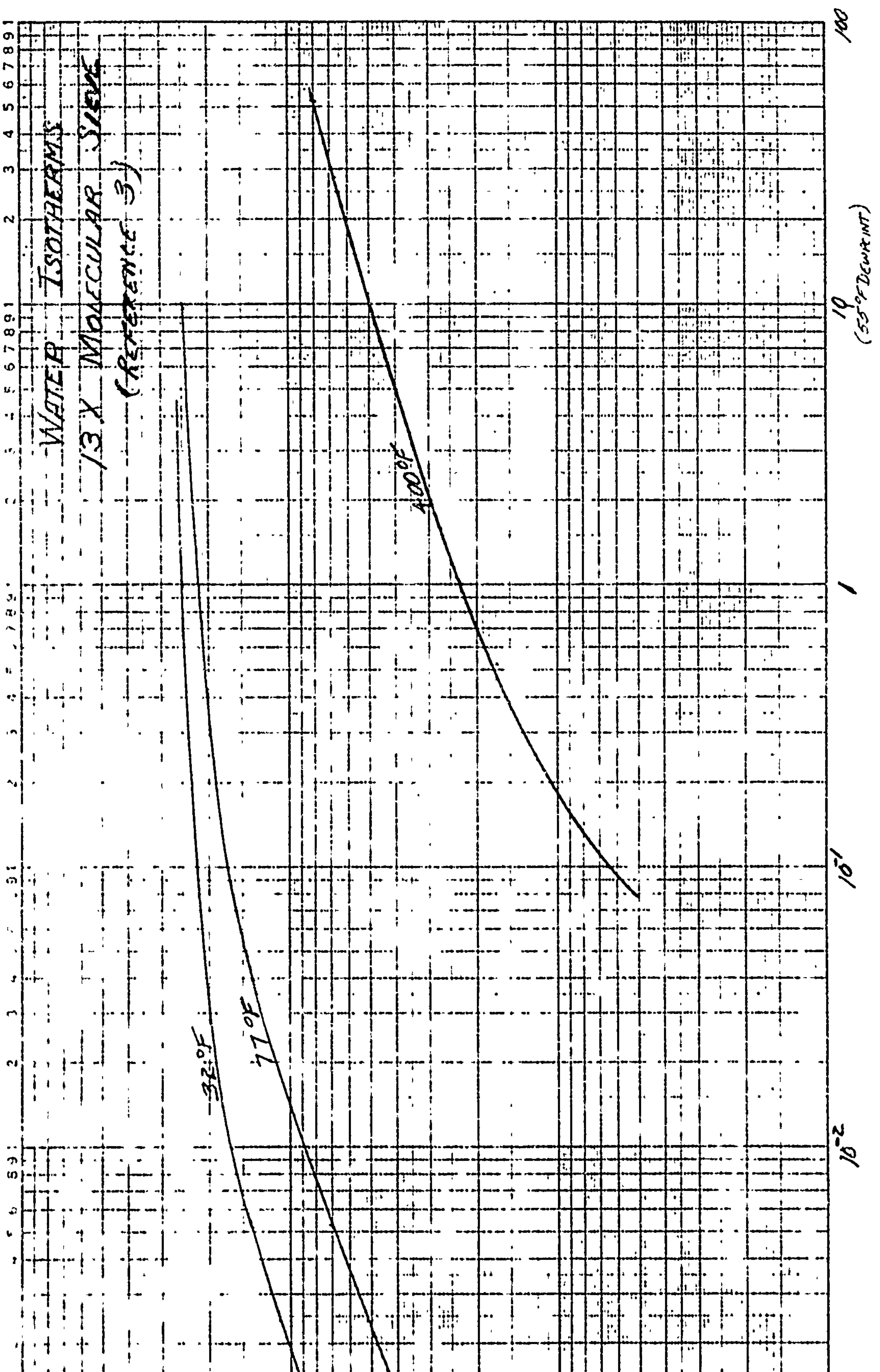
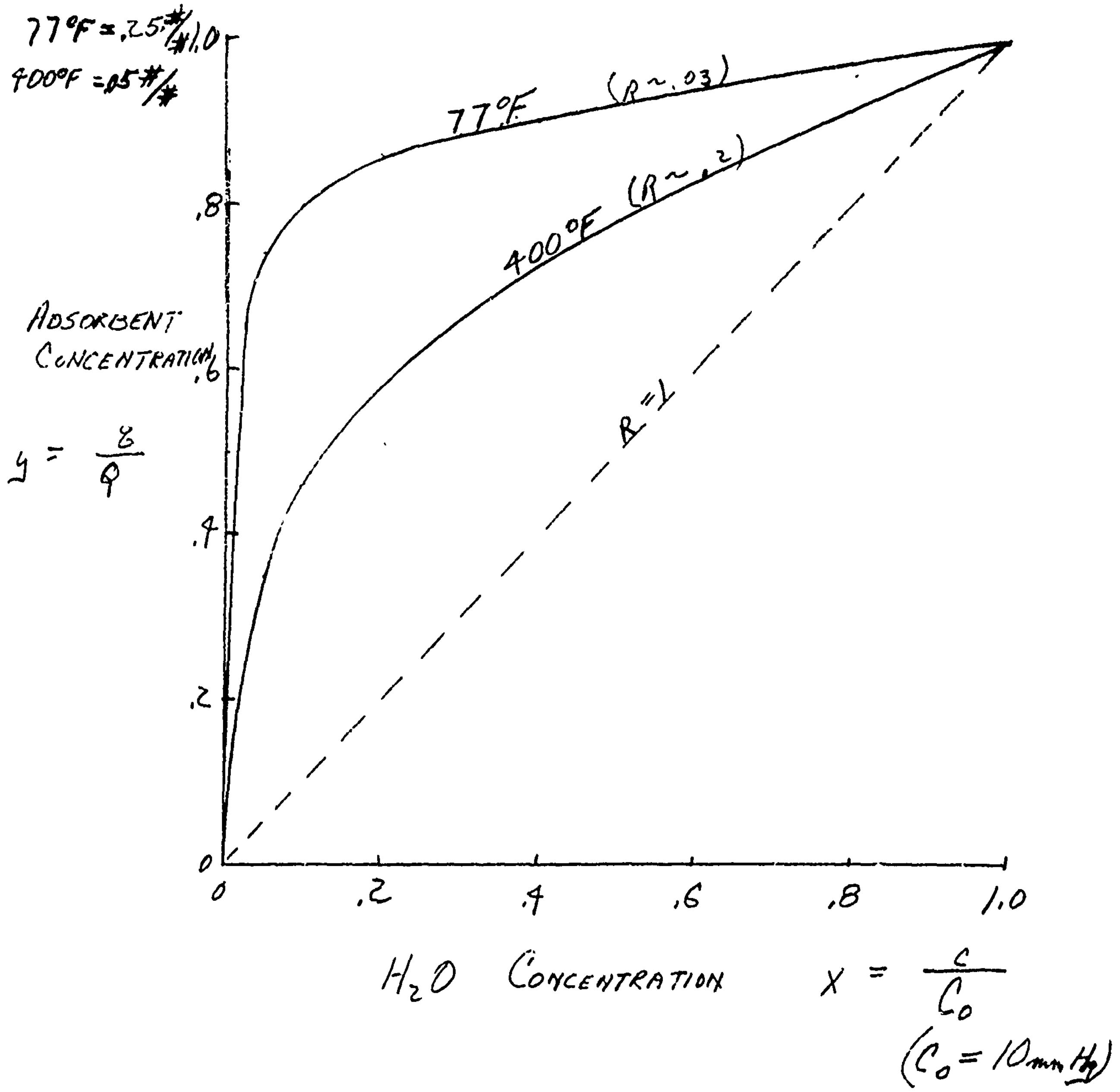

WATER ISOTHERMS
13X MOLECULAR SIEVE
(REFERENCE 3)
32°F
77°F
400°F
10^{-3}
10^{-2}
10^{-1}
1
10
(55°F DEW POINT)
100
P_{H_2O} - mm Hg
.1
1
10
100
H_2O / 100 # ADSORBENT

FIG III-1

TITLE: H_2O ADSORPTION ISOTHERMS
13 X MOLECULAR SIEVE

BY: **DATE:**



DIMENSIONLESS ISOTHERMS

13X MOLECULAR SIEVE

(DATA FROM UCC F-3036-3)

FIG IV-2

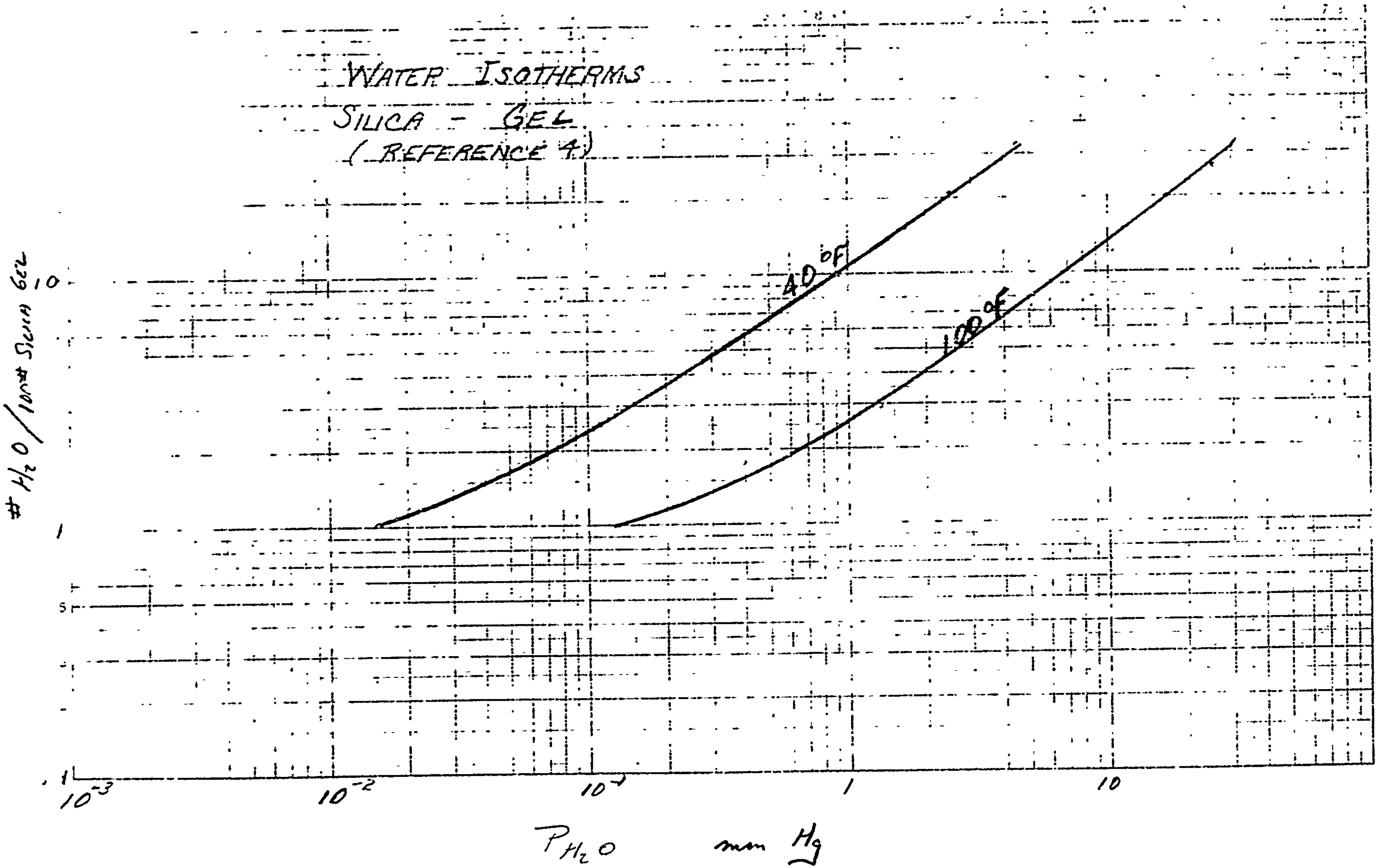
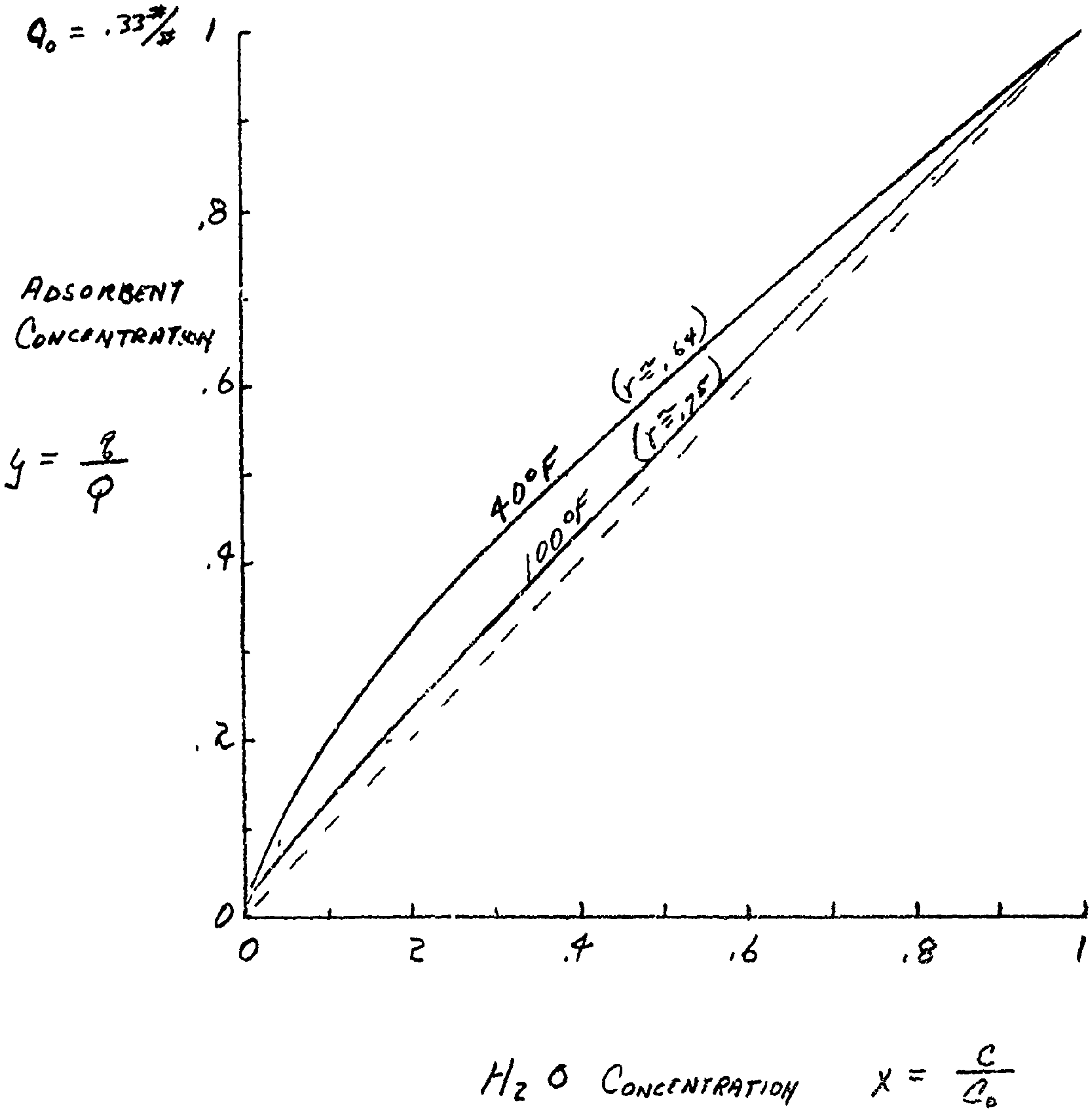

WATER ISOTHERMS
SILICA - GEL
(REFERENCE 4)
40 °F
100 °F
H_2O / 100# Silica Gel
10
1
5
.1
10^{-3}
10^{-2}
10^{-1}
1
10
P_{H_2O} mm Hg

FIG IV-3

JOHN M. CANTY, P. E.
ENGINEERING CONSULTANT
117 CORNWALL AVENUE
TONAWANDA, NEW YORK 14150
(716) 832-6554

TITLE: H_2O ADSORPTION ISOTHERMS
SILICA GEL

BY: ____________ **DATE:** ____________

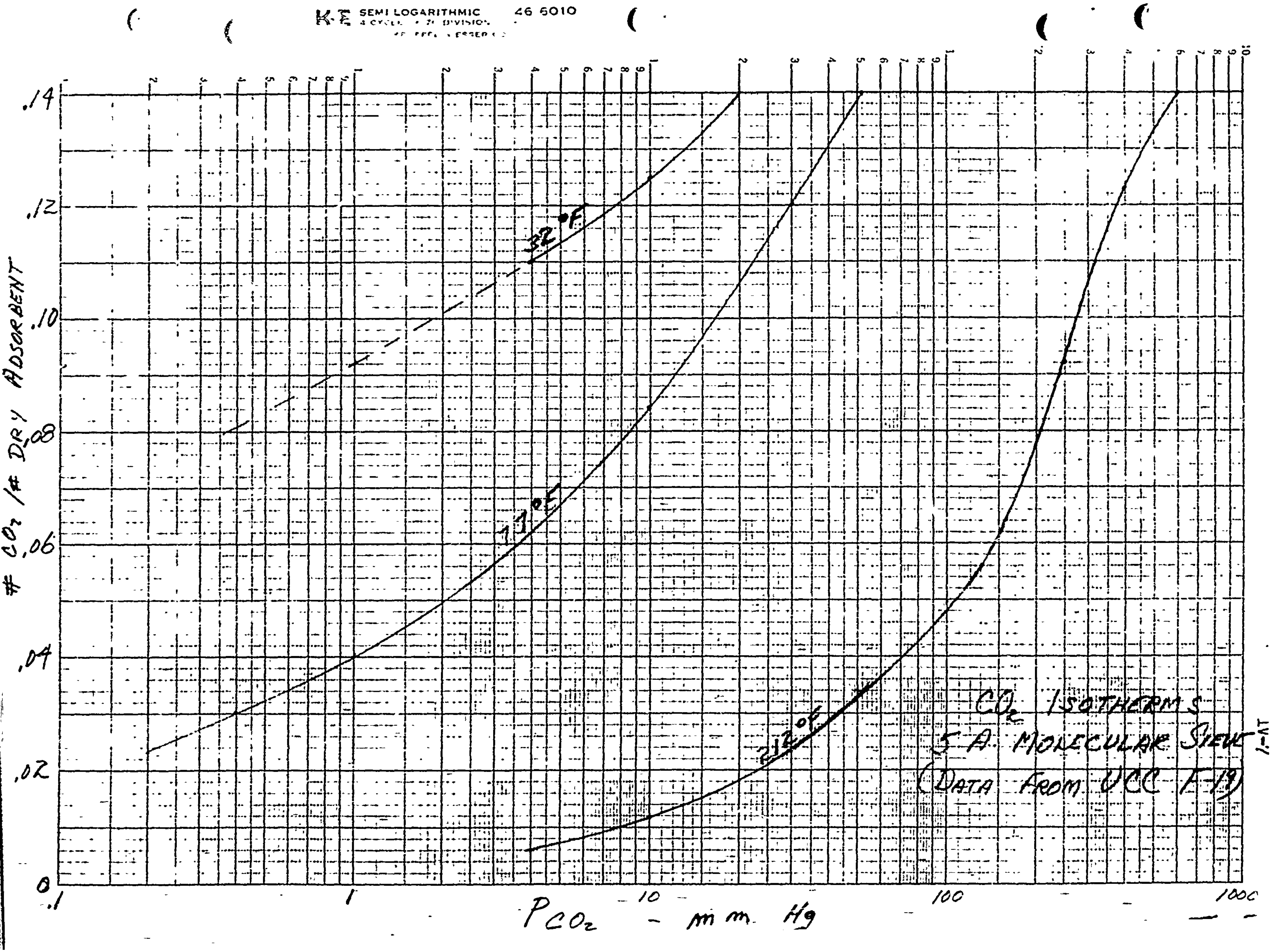


40°F $C_0 = 4.5$ mm Hg
100°F $C_0 = 33$ mm Hg

DIMENSIONLESS ISOTHERMS

SILICA GEL

(DATA FROM TECH BUL 202 - DAVISON DIV - W.R.GRACE)

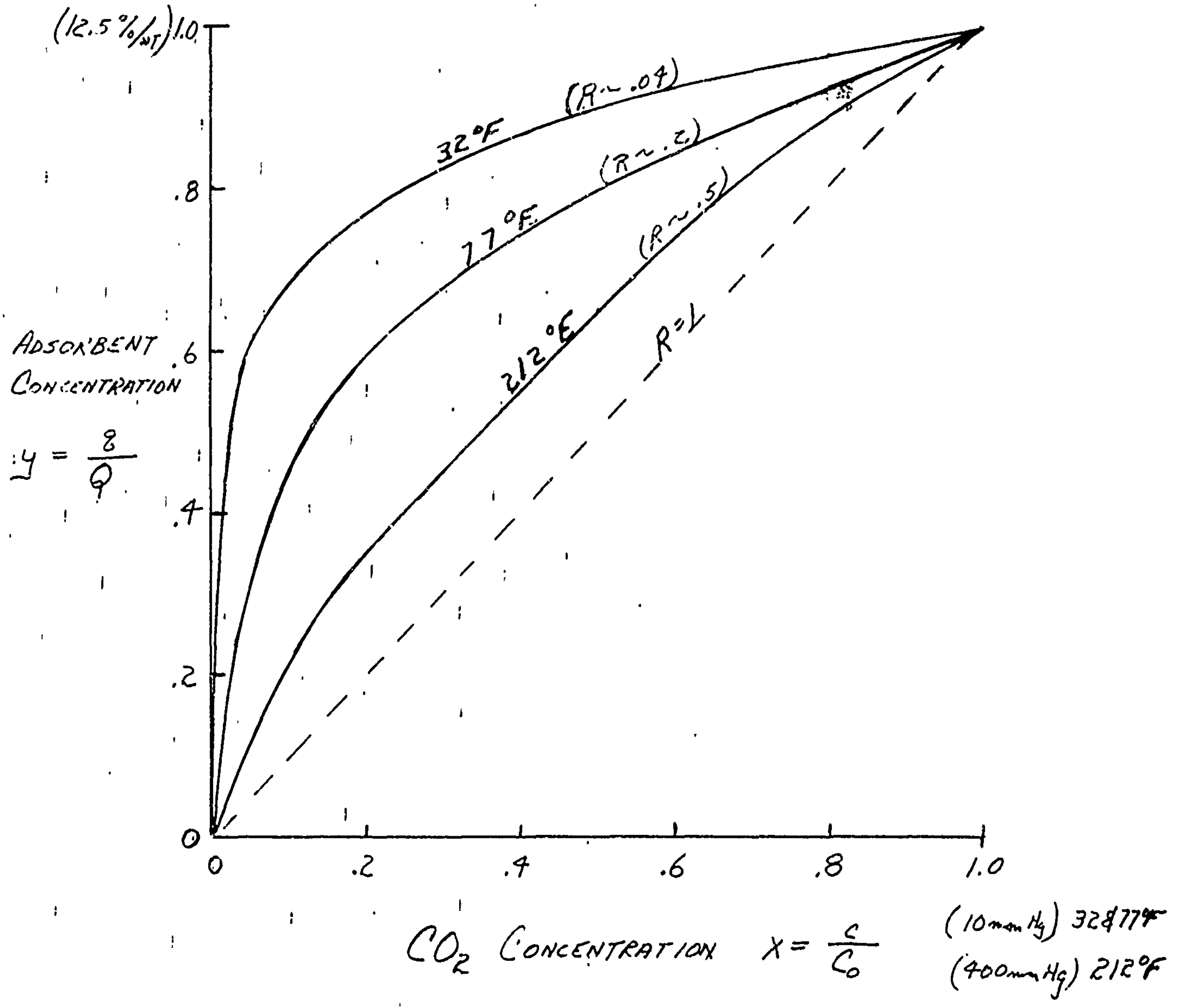


CO2 ISOTHERMS
5 A MOLECULAR SIEVE
(DATA FROM UCC F-19)

1-AT

TITLE: CO_2 Adsorption Isotherms
5 A Molecular Sieve

BY: **DATE:**



5-A Molecular Sieve
(Data From Union Carbide Corp.
F-19 "Linde Molecular Sieves")

Fig IV-6

F. Adsorption "Efficiency":

The effectiveness of an adsorbent depends on the ease with which the material being adsorbed can reach the adsorbent (a function of the diffusivity and void space of the bed), the contact time (a function of velocity and bed length) and the equilibrium curve characteristic.

The dimensionless parameter which relates these variables is called the Peclet Number:

$$P_e = \frac{d_p V_s}{D_v F}$$

where: d_p = Equivalent diameter of the adsorbent particle, ft.

V_s = Superficial velocity of bed (with no adsorbent), ft/sec

D_v = Diffusivity of the gases ft^2/sec

F = Fractional void space of adsorbent bed

When the Peclet number is greater than 20, the diffusion of the gas is controlling and the number of recation units can be determined by:

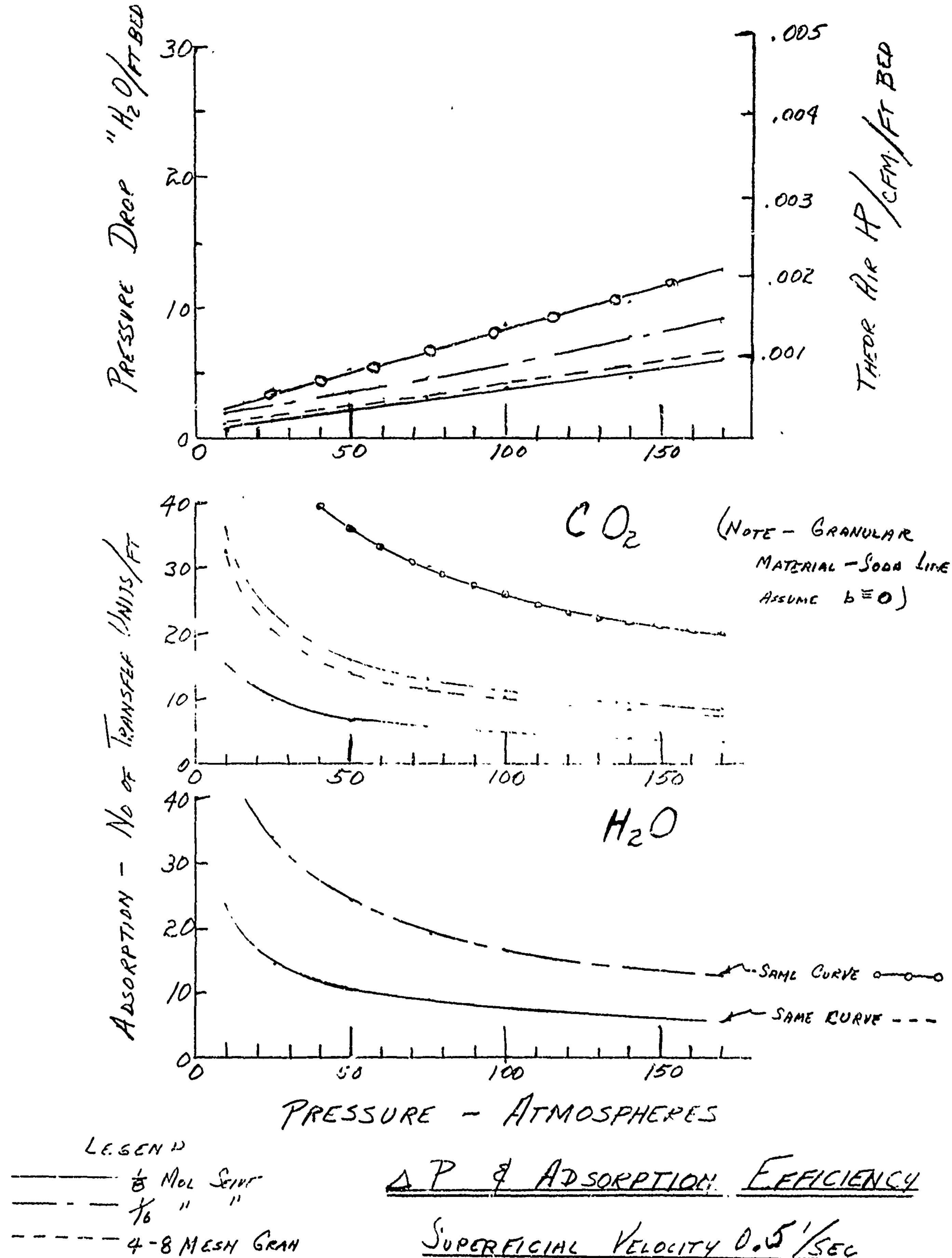
$$N = \frac{2.5\ b}{d_p\ P_e}$$

Where: N = Number of reaction units per ft. of bed (It is desirable to have a large number of reaction units since this will result in a much sharper "break through" curve, see Ref. 5)

b = Isotherm adsorption factor $= \frac{2}{1 + R}$

At a given temperature, the diffusivity varies inversely as the pressure. In the case of an adsorbent system for diving it is necessary to increase the contact time (either by reducing the velocity or increasing the bed length) to compensate for this. Another method of improving the adsorption efficiency is to decrease the particle size of the adsorbent at the penalty of a higher pressure drop.

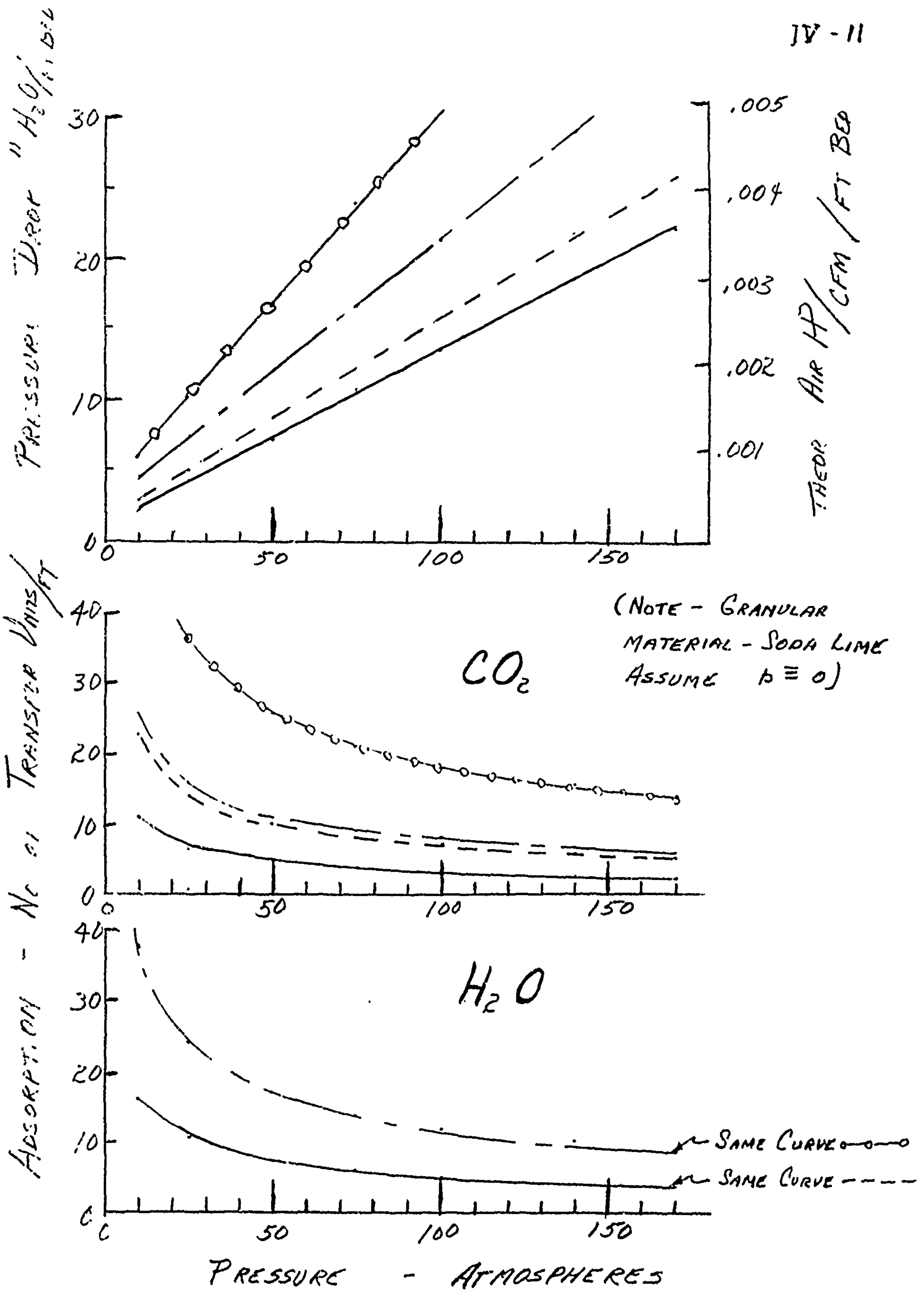
Figures IV-7, IV-8 and IV-9 show the number of reaction units per foot of adsorbent bed for superficial velocities of .5, 1 and 3 ft. per second and as a function of pressure (depth). Each graph shows values for water and for CO_2 for four adsorbents, 1/8 and 1/16 molecular sieve and 4-8 and 8-12 mesh granular material. The latter materials would be silica gel or activated alumina for water and soda lime or baraylyme for removing CO_2 (in this case it is a chemical reaction rather than adsorption but diffusion would be controlling). Values of pressure drop for each adsorbent as a function of pressure are also shown.



ΔP & Adsorption Efficiency

Superficial Velocity 0.5'/Sec

Fig IV-7

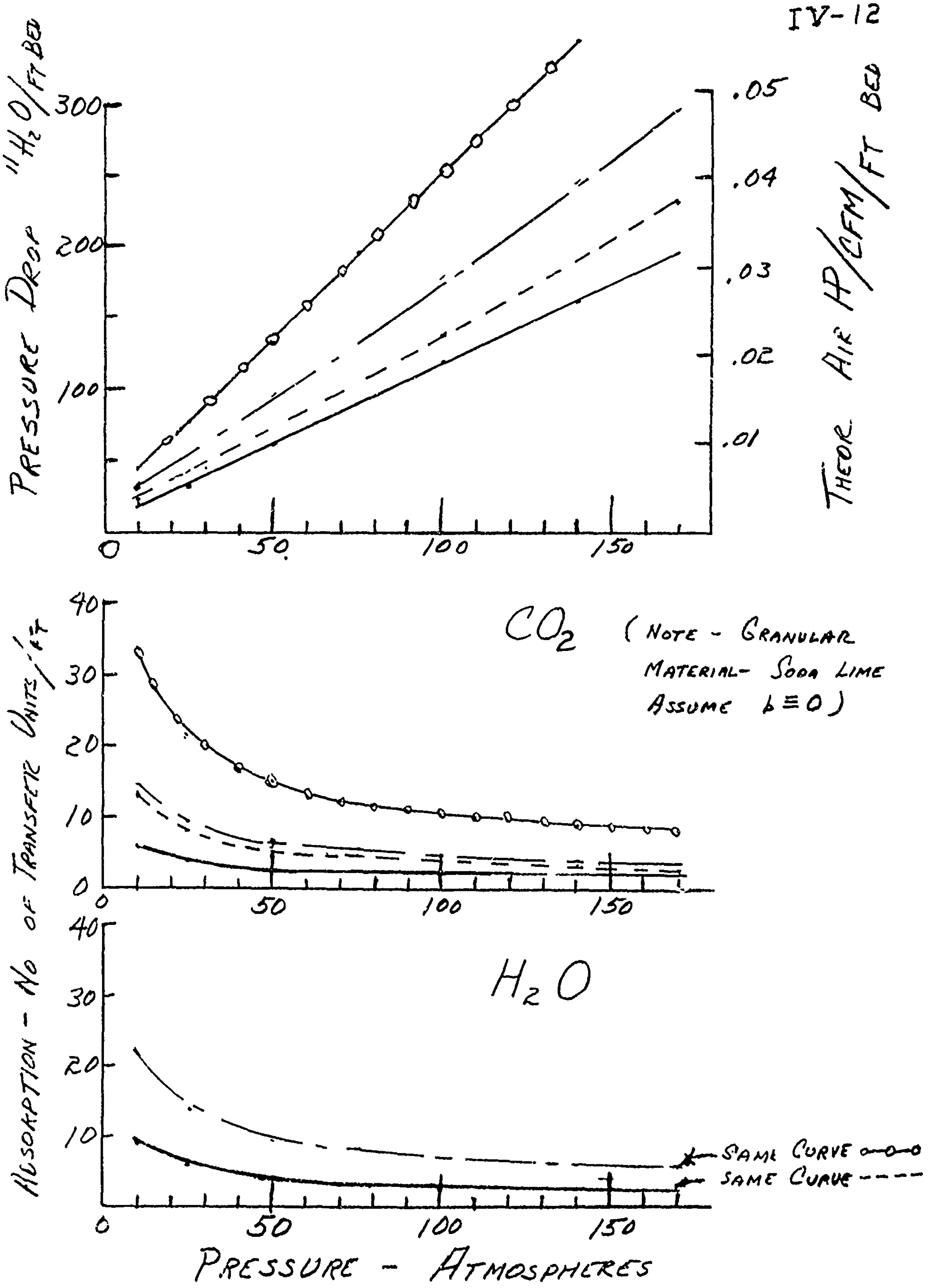


(Note - Granular Material - Soda Lime Assume $p \equiv 0$)

ΔP & Adsorption Efficiency

Superficial Vel 1 Ft/Sec

Fig IV-8



Legend
- ——— 1/8 Mol Seive
- — - — 1/16 " "
- - - - - 4-8 Mesh Gran
- o—o—o—o 8-14 " "

ΔP & Adsorption Efficiency

Superficial Velocity 3'/sec

Fig IV-9

References:

1. "Skylab Environmental Control and Life Support Systems" G. D. Hopson, J. W. Littles and W. C. Patterson. ASME Paper 71 AV-14 also Mechanical Engineering Vol. 94, No. 5, May 1972, p 35-40.

2. "A Regenerative Carbon Dioxide Removal System for the AAP Cluster" J. P. Gillerman, SAE paper 690626, National Aeronautics and Space Engineering and Manufacturing Meeting, Los Angeles, Calif. October 6-10, 1969.

3. Linde Molecular Sieves - Water and Air Data Sheets #F3035 - Union Carbide Corp.

4. Technical Bulletin 202, Davison Chemical Div., W. R. Grace & Co.

5. "Chemical Engineers Handbook", R. H. Perry, C. H. Chilton, S. D. Kirkpatrick, 4th Edition, Section 16.

V. Comparison of Low Temperature, Adsorption and Chemical Removal Systems

A. General:

The results given in this section of the report pertain to evaluation of a three man module using 18 cfm gas flow. Information given in the physiological portion of this report (Section I) indicates that this provides an expected level of CO_2 pressure ranging between 1.2 millimeters of mercury and 4 millimeters of mercury. The following design parameters were used in the evaluation of the environmental control system:

Pressure - 10 atmospheres to 170 atmospheres

Chamber volume - Sphere 180 cu. ft.
Cylindrical section 540 cu. ft.

Dry bulb temperature - 85°F

Relative humidity - 50%

Gas - Helium + 1/2 ATA O_2

Although the results given in this section are specific to the High Pressure Research Facility at the State University of New York at Buffalo, data given in the balance of the report are presented in a general way so that they can be extrapolated for the design of other systems with different flow rates and chamber sizes.

B. Cooling to Remove CO_2:

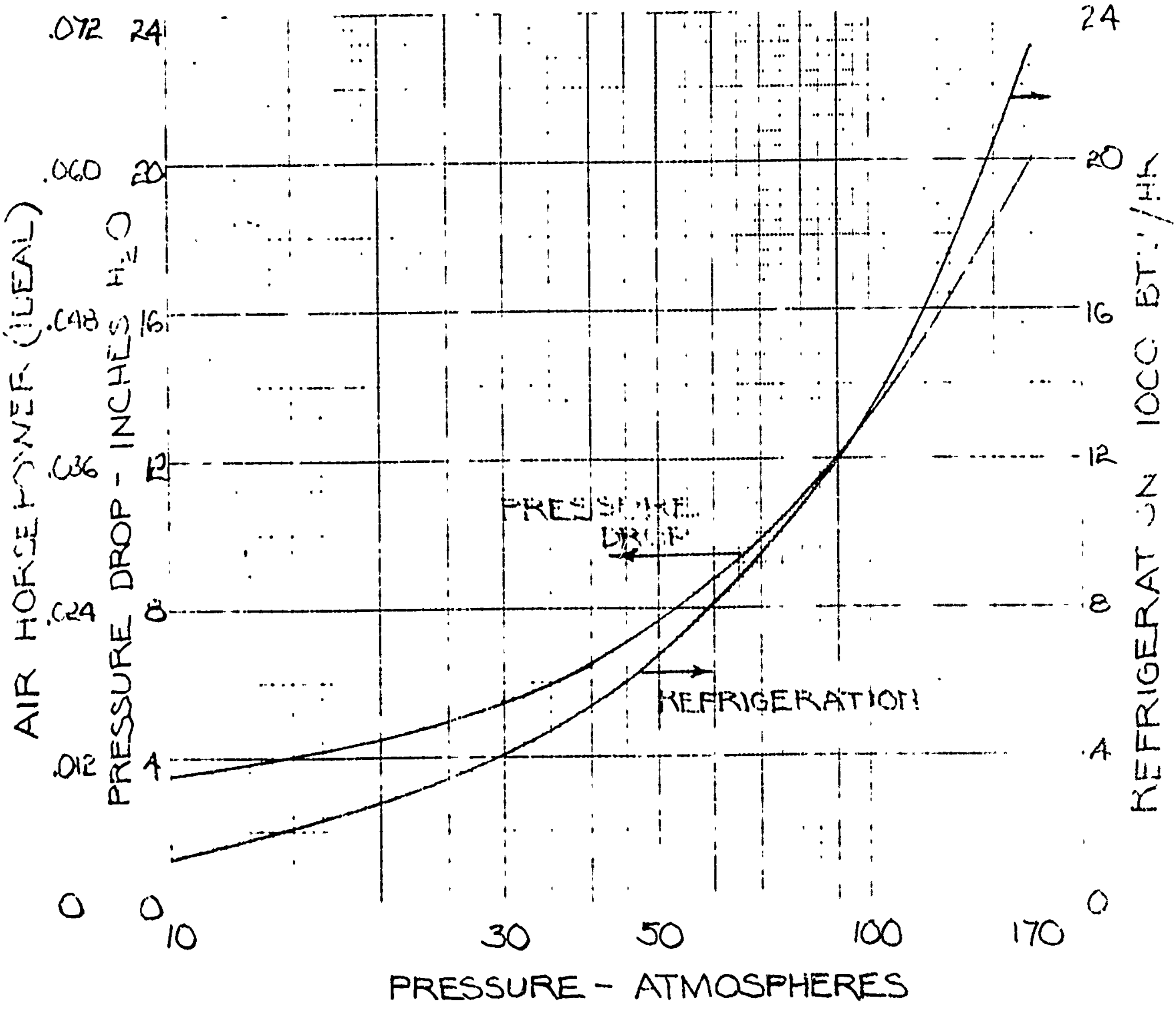
The use of a compact counterflow heat exchanger to cool the gas and remove water and CO_2 has the advantage that no high pressure equipment is required if the heat exchanger is kept within the confines of the chamber environment.

Functionally this is the simplest of all systems. However, it requires a source of very low temperature refrigeration since the carbon dioxide will not start to condense until the temperature reaches -190°F. A 10° temperature drop across the refrigeration portion of the equipment is necessary to condense most of the CO_2 and to provide an adequate "driving force" for the heat exchanger.

The results for a three man module are shown in Fig. V-1. Design data for compact heat exchangers is given in Section III.

Where the refrigeration is available this could be a very promising system for pressures up to 30 atmospheres (about 1,000 ft. of depth). However, the refrigeration requirement becomes prohibitive at very high pressures. It is necessary to add an amount of heat to the chamber

SERRATED FIN
7¾' LONG, 5"×5" CROSS SECTION
VEL. - 4'/SEC FLOW - 18 CFM
ΔT - 10° F.



HEAT EXCHANGER - CO_2 REMOVAL
3 MAN MODULE

FIG. V-1

equivalent to the refrigeration supplied in order to avoid lowering the overall chamber temperature (the heat of condensation of H_2O and CO_2 contributed very little in this case). This heat is in addition to that required due to heat loss of the walls of the chamber or habitat.

A system similar to this has been proposed for space applications, and some test results are available indicating that it is technically feasible (see Ref. 1). The results shows that CO_2 can be condensed and revaporized at 1 atmosphere. Since the diffusivity of the gas is inversely proportional to pressure, additional test work needs to be done at high pressures to verify the efficacy of removing CO_2 under these conditions.

C. Cooling for Humidity Control:

Cooling the gas to remove water appears to be a practical method. Standard refrigeration equipment (e.g. Freon) can be used to remove heat to maintain the temperature difference. Countercurrent heat exchangers are also indicated for this cooling to reduce the total refrigeration requirements and size of the cooling coils.

The resulting pressure drop and refrigeration requirements for a three man 18 cfm module cooling the gas to 32°F is shown in Fig. V-2. This is based on a driving force across the heat exchanger of 3°F. It is possible to reduce the length of the heat exchanger by increasing the temperature difference at some penalty in refrigeration power cost and increased replacement of heat.

D. Humidity Control by Adsorption:

Water can be removed from the air by use of silica gel, activated alumina, or molecular sieve. Silica gel has a very high capacity for water and can be reactivated at a relatively low temperature. However, it will not produce the very low dewpoint that is attainable through the use of fresh molecular sieve.

When using an adsorbent to control humidity, the air will become too dry if all of the gas from an 18 cfm module is passed through the adsorbent. (See Section I, Fig. I-2) In this case it will be necessary to rehumidify the air either by returning some of the moisture laden gas to the vessel when the adsorbent is reactivated or by separate humidification of the gas downstream of the adsorber.

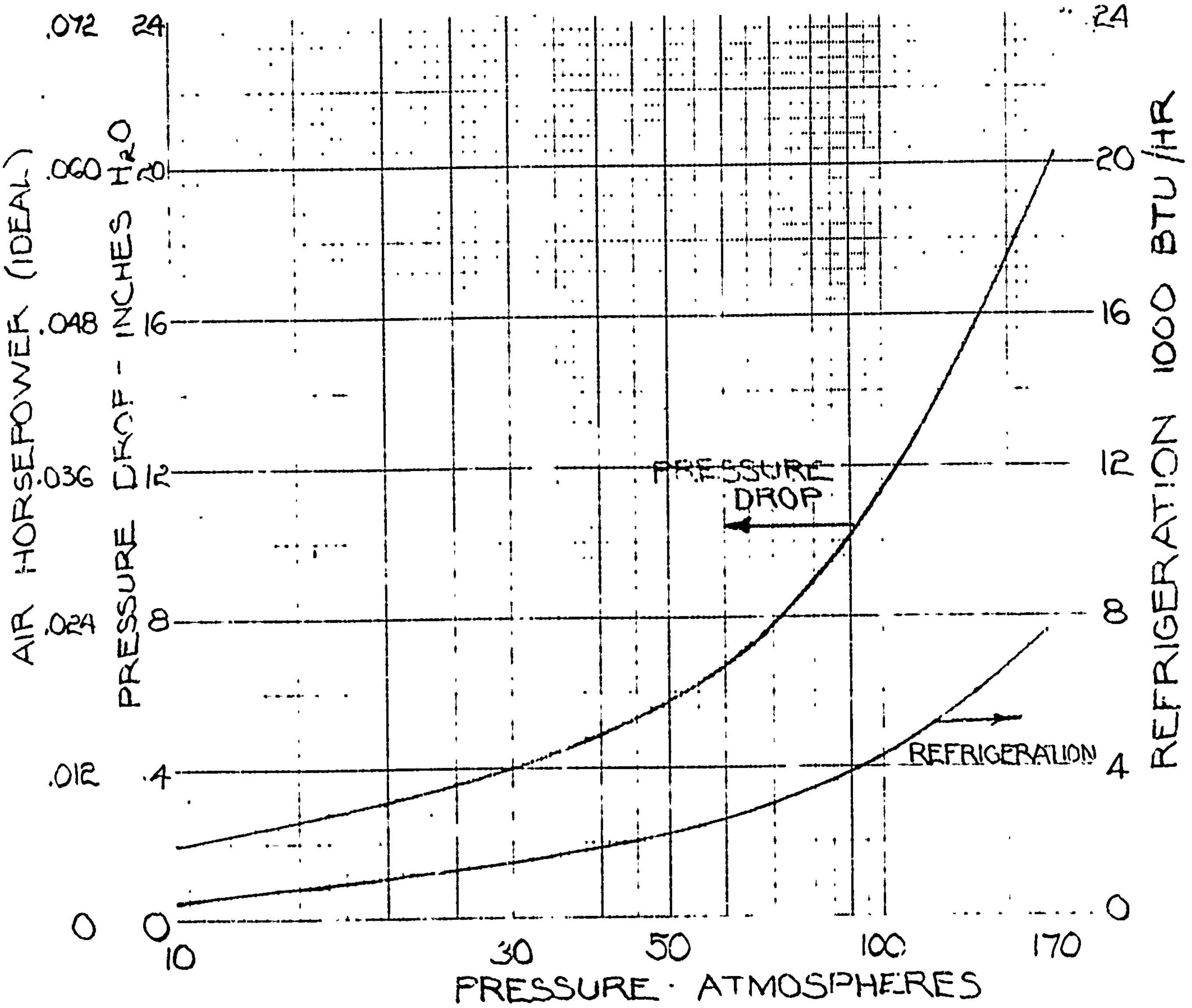
An alternative to this would be to circulate only a part of the gas through the drier section of the environment control system.

Pressure drop and adsorbent capacities for water of various materials are given in Section IV of this report.

E. CO_2 Removal by Adsorption:

The use of an adsorbent to remove carbon dioxide is attractive in that

SERRATED FIN
5½' LONG, 5"×5" CROSS SECTION
VEL. - 4'/SEC FLOW - 18 CFM
ΔT - 3° F.



HEAT EXCHANGE DEHUMIDIFICATION
3 MAN MODULE

FIG. V-2

the system can be regenerated, eliminating the need to replenish the material as is necessary in a chemical removal system. (Baralyme or soda lime) The material most suitable for adsorption of CO_2 appears to be 5A Molecular Sieve. (Linde Div., Union Carbide Corp. Type 5A Molecular Sieve).

In order to effectively remove CO_2 by adsorption it is necessary to have extremely dry gas since molecular sieve will preferentially adsorb moisture. Moisture in a gas will displace any CO_2 that has been adsorbed. Therefore the gas must remain dry until the CO_2 is desorbed. A system using molecular sieve is being used in submarines by the French and by Great Britain. The main disadvantage of this type of system is that it usually requires a very high reactivation temperature in order to effectively remove all of the water (500 to 600°F).

An interesting cycle using adiabatic desorption has been proposed for a space application (see Ref. 2 and 3). Essentially this is a method of using the adsorbent inefficiently with regard to the pounds of material adsorbed per pound of adsorbent. A "pressure swing" cycle is used, reducing the adsorbent bed pressure to desorb CO_2 and recycling very frequently. In this case a 15 minute cycle adsorb-desorb cycle was used. The readily available vacuum of space simplified the equipment required.

The test results shown in Ref. 2 are interesting in that this system effectively moved moisture and maintained a system outlet partial pressure of CO_2 less than 1-1/2 millimeters for more than two months test time all without the need for a high temperature reactivation. The data would seem to indicate a moderate temperature-pressure swing cycle might be used very effectively to enhance the adsorption capability of such a system.

In addition, some tests of this unit made at the Marshall Space Center, Huntsville, have indicated the removal of Ammonia, Methyl Chloride and other trace contaminants. Carbon monoxide and Hydrogen were also tested but not adsorbed, as might be expected due to the low critical temperatures of these gases.

Data on adsorption capacity and pressure drop for 5A Molecular Sieve is given in Section IV of this report.

F. CO_2 Removal by Chemucal Reaction:

The most common method of removing CO_2 is by recirculating the gas through a chemical that will react with the carbon dioxide (usually baralyme or soda lime).

These materials are effective and will be used as a "back-up" purification system for the High Pressure Research Facility. In the case of chemical reaction, water will be liberated. Therefore any humidity removal system should be placed downstream of the reaction. A cu. ft. of water vapor is produced for every cubic foot of carbon dioxide gas removed from the air for baralyme, soda lime and lithium hydroxide.

Although the data varies somewhat, it appears that the usual efficiency of baralyme or soda lime will result in a capacity of 20 lbs. of CO_2 per hundred pounds of chemical (see Ref. 4 and 5). Therefore, for a three man mission generating 12 lbs. of CO_2 per day, 60 lbs. per day would be required (about 1 cu. ft.). Data on pressure drop and transfer rate for solid granular chemicals is given in Section IV.

G. System Blower:

The 18 cfm system does not require very stringent performance from the air compressor. Several commercially available blowers would satisfy the capacity and pressure head requirements. However, these have the disadvantage of very high noise level and relatively large bulk. In addition, since blowers are usually designed for air at one atmosphere, a larger motor will be required for the more dense gas at high pressure.

There are several small blowers used for pipe organs designed to be very quiet. This is accomplished by careful design of the impeller and care in balancing the blower-motor unit. In addition sound adsorbing material is placed at critical places in the stream flow. While these would be acceptable from a noise and performance standpoint, the motor and materials of construction are not considered acceptable in the confined high pressure environment of a diving chamber.

It is proposed that a positive displacement, low pressure pump would be most suitable to this application due to the low flow that is required. This could be in the form of a multiple cylinder compressor or a bellows type system. Since this operates at low speed, the noise level should be very acceptable. A second advantage of this approach is that it could be manually operable for emergency use in case the diving system would fail.

A magnetically coupled drive will be used in the University High Pressure Research Facility. This will have the motor and all wiring located outside of the chamber and coupled to the blower (or crank) directly or by means of a pulley system within the pressure vessel.

References:

1. "An Experimental Investigation and System Design for Humidity and Carbon Dioxide Level Control Using Thermal Radiation", John S. Maulbetsch, AMRL-TR-68-174. Available from Clearinghouse, CFSTI, 5285 Port Royal Rd., Springfield, VA 22151.

2. Joseph B. Gillerman "A Regenerative Carbon Dioxide Removal System for the AAP Cluster". Society of Automotive Engineers Paper 690626 presented at National Aeronautic and Space Engineering & Manufacturing Meeting, Los Angeles, California Oct. 6-10, 1969.

3. "Skylab - Part 3 - Life Support Systems," G. D. Hopson, J. W. Littles and W. C. Patterson, Mechanical Engineering Vol. 94, No. 5 May 1972 pp 35-40.

4. "Soda Lime Handbook", Malliuckrodt Chemical Works, St. Louis, Missouri.

5. "A Study of Carbon Dioxide Gas Adsorption" National Cylinder Gas, 840 North Michigan Ave., Chicago, Illinois 60611.

VI. Recommended System and Program
SUNYAB - High Pressure Research Facility

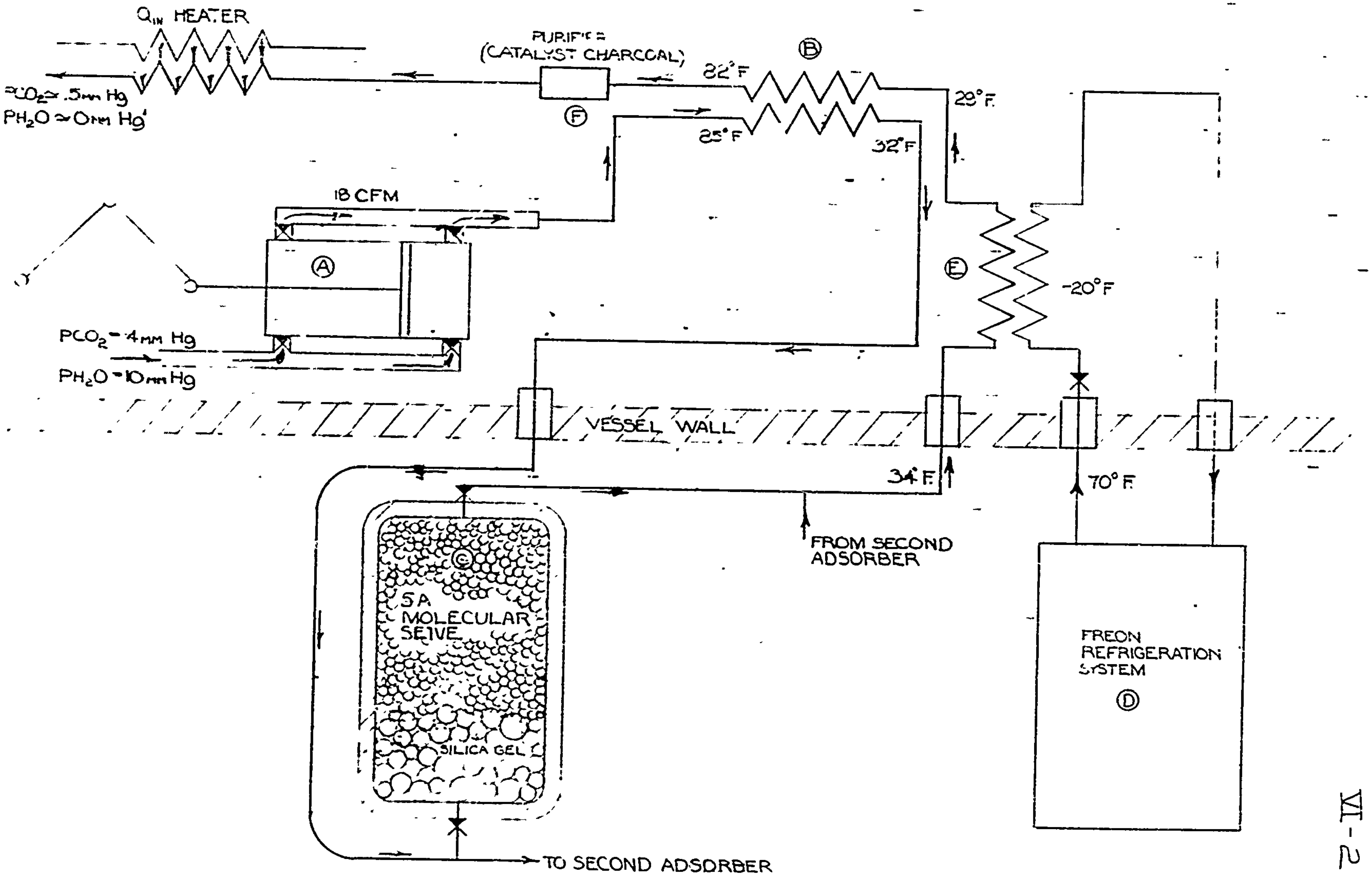
A. Main System:

The main flow loop for removal of CO_2 and control of humidity is a combination system. A countercurrent heat exchanger is used to remove some of the water and to lower the temperature of the gas flowing to the adsorbent bed. Silica gel is used to remove essentially all of the remaining water. The capacity of the silica gel is enhanced at the 33°F gas temperature by a factor of 3 to 5 times over the equivalent capacity at 85°F. Following the silica gel and in the same adsorbent bed is a large section containing Type 5A Molecular Sieve to remove carbon dioxide. Refrigeration is supplied after the adsorbent bed using a conventional freon refrigeration unit. Locating the cooler downstream of the adsorber permits cooling the gas below the freezing point without the difficulty of having to defrost the cooler. The cold gas is returned to the countercurrent heat exchanger where it is warmed almost to chamber temperature, passed through a small bed of Hopcolite and charcoal, and returned to the chamber. Heat will be added to the chamber (in the heater coil) to make up for the heat removed by the cooling coil. The environment control system is shown schematically in Fig. VI-1.

The heat exchanger and cooling sections are located within the high pressure vessel, thus permitting the use of standard aluminum plate and fin heat exchangers for the countercurrent exchanger and light wall vessel for the cooler. Originally, it was planned to locate the adsorbent beds within the chamber. However, it was found that there would be no saving in weight since these adsorbent beds will be vacuum pumped and would have to be designed for high external pressure if located inside. The additional pressure drop to flow through the piping in the vessel wall is not prohibitive because of the low flows involved and small piping and valves (1-1/4 PS) can be used. Other advantages in locating the units on the outside of the chamber are saving of valuable test space, ease of reacting, and the improvement of insulation around the adsorbent due to the lower thermal conductivity of air compared to helium.

Reactivation of the adsorbent bed is unconventional. Initially the adsorbent bed gas will be vented into a storage receiver. Since most of the water and CO_2 will be held on the adsorbent the residual gas will be essentially all helium and oxygen and can be recompressed and returned to the chamber or to storage banks. The adsorbent bed will be repressurized with helium or a helium-oxygen mixture before returning it to the control loop. This will avoid a change in chamber pressure when switching adsorbers.

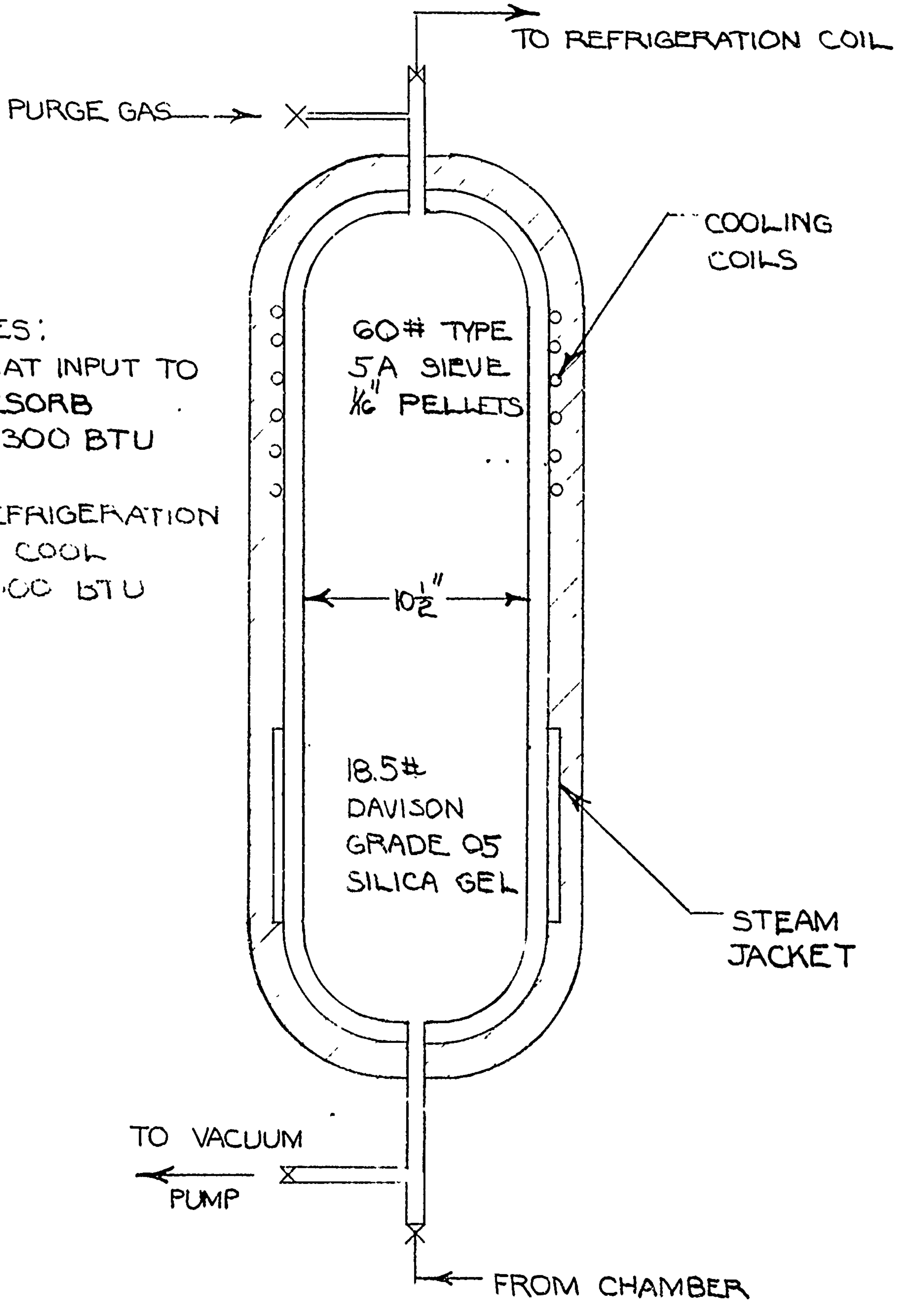
When the pressure has been reduced to atmospheric, the bed will be heated and vacuum pumped to remove the adsorbed water and CO_2. With



SCHEMATIC—MAIN SYSTEM FIG. VI-1

FIG VI-2

DESORBTION CYCLE



NOTES:

HEAT INPUT TO DESORB 15,300 BTU

REFRIGERATION TO COOL 6000 BTU

vacuum pumping, only a modest temperature (100 to 150°F) will be required to recondition the adsorbents. A small gas purge of dry nitrogen will be introduced to maintain the adsorbent bed pressure above the transition pressure of the silica gel (about 2 mm Hg). This will assure a flow of gas and contaminents out of the bed through the silica gel end and eliminate back flow of moisture to the Molecular Sieve. A gas ballast vacuum pump or cold trap will be required to prevent contamination of the vacuum pump with the large amount of water vapor being pumped from the bed. The reactivation cycle is shown diagramatically in Fig. IV-2.

The control loop will be sized for a three man module. This will use 18 cfm during the day time, resulting in an expected CO_2 level between 2.4 and 4 mm of Hg. At night the system will run at one-half flow, 9 cfm. The lower flow will reduce the refrigeration requirement and have a lower noise level. Nine cfm will result in a CO_2 level of just under 2 mm Hg due to the lower metabolic rate when the occupants are sleeping (see Fig. I-1).

The basic calculations for the main system heat exchanger and adsorber design are appended to this section.

B. Pass Through Lock Module - High Pressure Research Chamber:

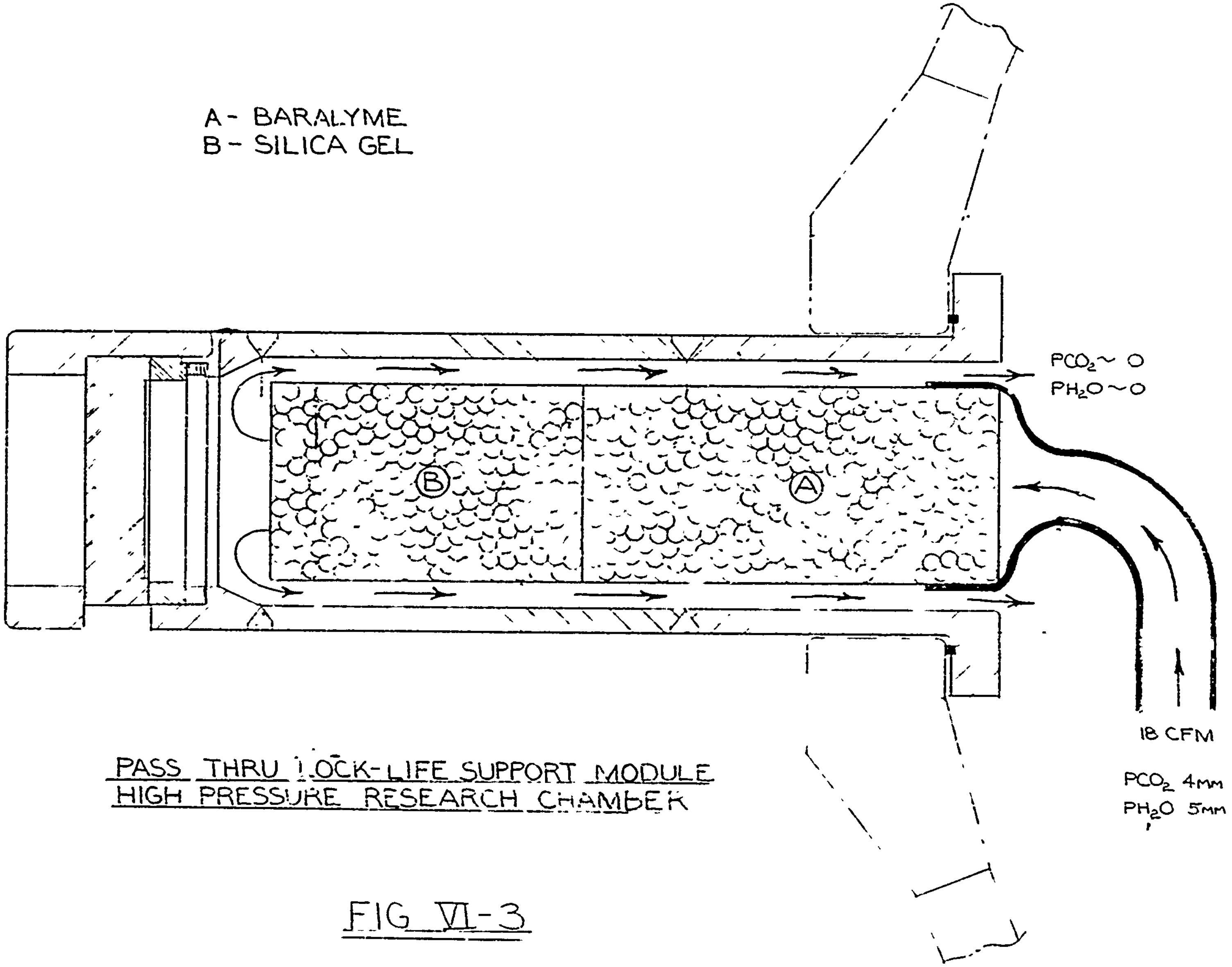
A back up system to remove CO_2 in the event of the primary system failure is shown in Fig. VI-3. This again is a "half day" charge using baralyme to remove carbon dioxide and silica gel to remove part of the water. The back up system canister will be inserted in the pass through lock. In the case of manned chamber occupancy the connection to the module can be made manually after pressurising and opening the lock inner door. For animal experimentation, it will be necessary to perform these operations remotely from outside of the chamber. Calculations on adsorbent capacity are appended to this section.

An alternate system using a blower in place of the silica gel section will be designed for use in the event of failure of the primary blower or magnetic drive in the chamber.

C. Future Program:

Small scale tests are needed to verify the "breakthrough" characteristics of the silica gel-molecular sieve combination. This will include tests at 10, 50 and 100 atmospheres pressure using 1/2 atmosphere pressure O_2, 4 mm Hg CO_2, 5 mm Hg H_2O and helium.

This gas will be cooled to 32°F and passed through a sample cylinder containing the appropriate ratio of silica gel and molecular sieve sections. The gas will be analyzed at the end of the silica gel and at the outlet for pressure of CO_2 and H_2O. The sample bottle will then be heated to 100 - 120°F and desorbed, followed by cooling and another test. This will be continued until the adsorbent capacity



PASS THRU LOCK-LIFE SUPPORT MODULE
HIGH PRESSURE RESEARCH CHAMBER

FIG VI-3

shows signs of deterioration.

Figure VI-4 shows the test arrangement. The estimated cost for this work is:

Apparatus	Design	$ 400.00
	Purchase	600.00
Gases & Liquid Nitrogen		200.00
Technician 4 weeks		1600.00
Analysis of results		600.00
	Total	$3400.00

Detail design of the heat exchangers, pressure vessels, blower and refrigeration system along with the interconnecting piping must be completed prior to procurement and installation. The estimated cost of the equipment and design is (letters refer to items on Figure VI-1):

A.	Blower or Pump	$ 500.00
B.	Plate and fin heat exchanger	2,200.00
C.	Adsorbent bed (2 required @ 1200)	2,400.00
D.	Refrigeration system	800.00
E.	Cooler Heat Exchanger	600.00
F.	Purifier	300.00
	Vacuum Pump	600.00
	Piping, fittings and valves	600.00
	Total Parts	$ 8,000.00
	Design	1,400.00
		$ 9,400.00
	Assembly & Installation (Technician 4 weeks)	1,600.00
	Total	$11,000.00

shows signs of deterioration.

Figure VI-4 shows the test arrangement. The estimated cost for this work is:

Apparatus	Design	$ 400.00
	Purchase	600.00
Gases & Liquid Nitrogen		200.00
Technician 4 weeks		1600.00
Analysis of results		600.00
	Total	$3400.00

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A.	Blower or Pump	$ 500.00
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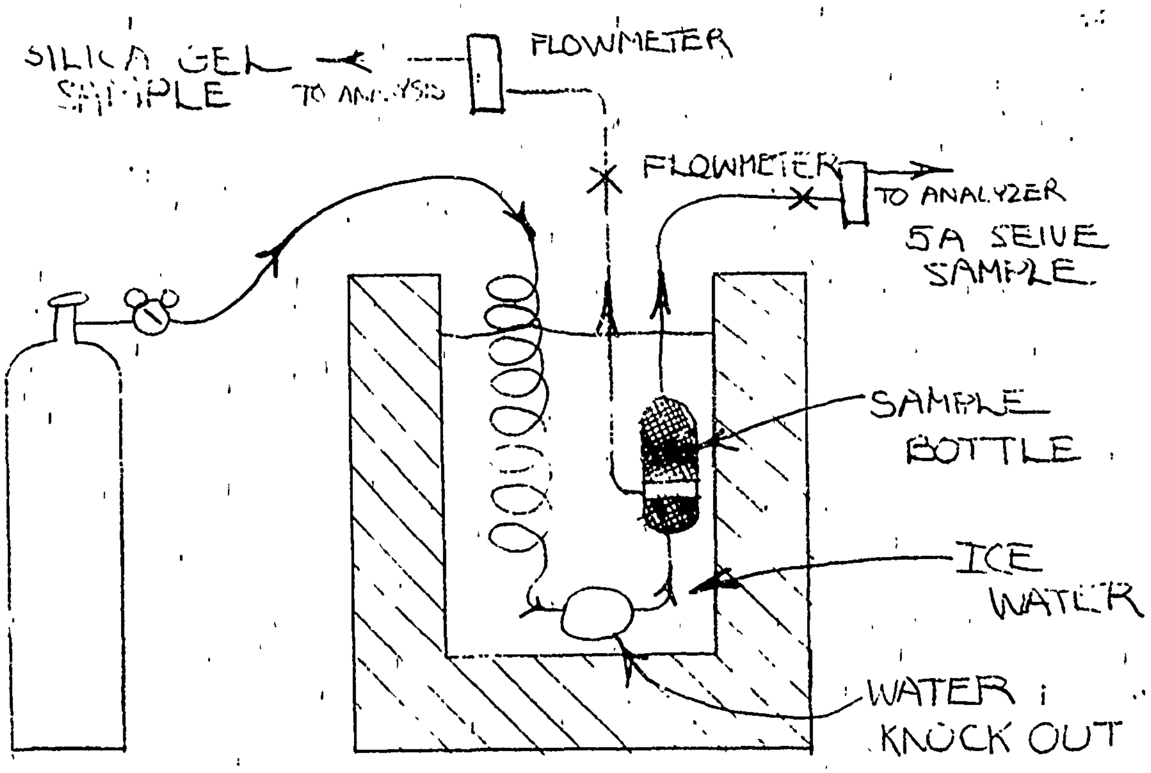
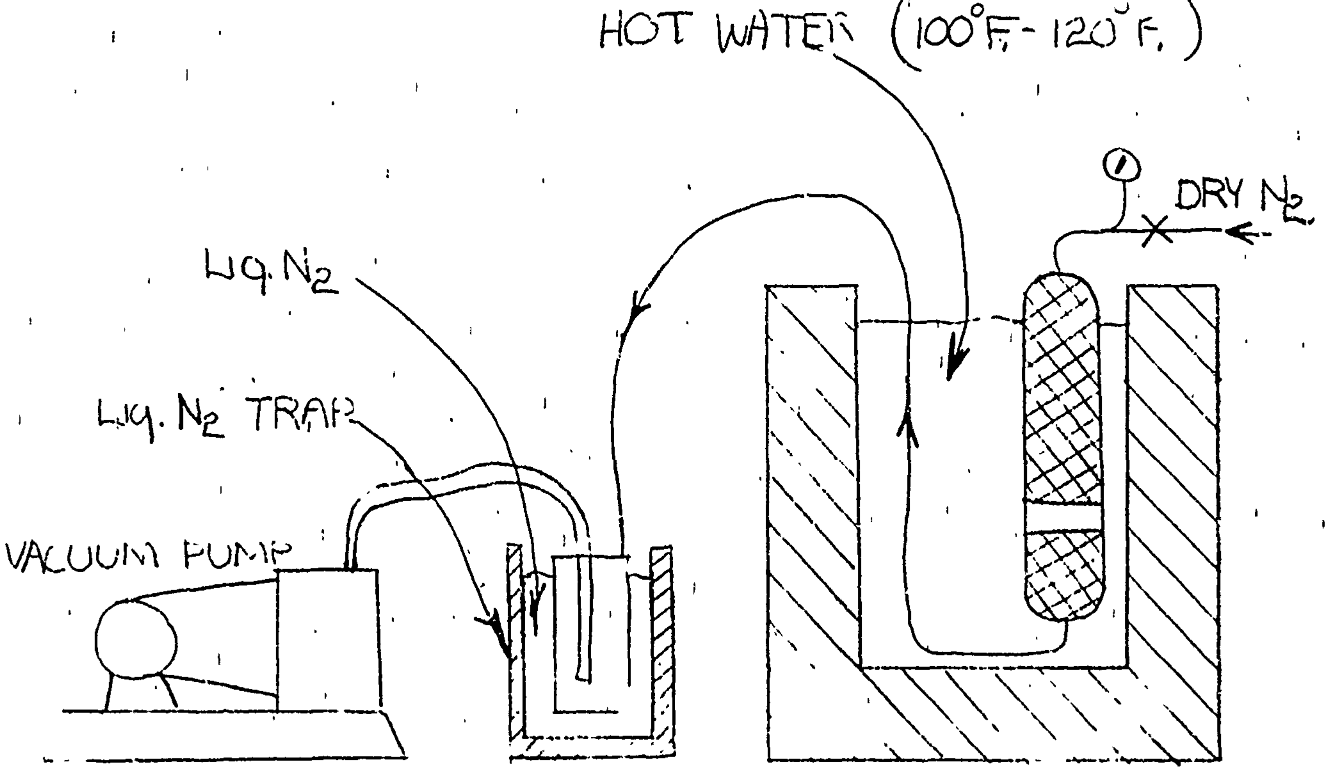
C.	Adsorbent bed (2 required @ 1200)	2,400.00
D.	Refrigeration system	800.00
E.	Cooler Heat Exchanger	600.00
F.	Purifier	300.00
	Vacuum Pump	600.00
	Piping, fittings and valves	600.00
	Total Parts	$ 8,000.00
	Design	1,400.00
		$ 9,400.00
	Assembly & Installation (Technician 4 weeks)	1,600.00
	Total	$11,000.00



ADSORBTION CYCLE



DESORBTION CYCLE

FIG. VI-4

SMALL SCALE ADSORBENT CAPACITY TEST

TITLE: ENVIRONMENTAL CONDITIONING LOOP DESIGN CALCULATIONS.
BY: JMC DATE:

JOHN M. CANTY, P. E.
ENGINEERING CONSULTANT
117 CORNWALL AVENUE
TONAWANDA, NEW YORK 14150
(716) 832-6554

OPERATING CONDITIONS:

3 MAN MODULE - EACH MAN (SEE TABLE I-1)

WORK	HRS/DAY	CO_2		H_2O		O_2	
		#/hr	#/Day	#/hr	#/Day	std cu ft/hr	std cu ft/Day
HEAVY	6	.38	2.3	.18	1.08	3.75	22.5
LIGHT	10	.13	1.3	.061	.61	1.3	13.0
SLEEP	8	.06	.6	.023	.18	.63	5.1
	TOTAL		4.1#/DAY		1.87#/DAY		40.6 cu ft/Day

FOR 3 MEN -

AVE DAYTIME $CO_2 = \frac{3(2.3+1.3)}{6+10} = .675$ #/hr

* " " $H_2O = \frac{3(1.08+.61)}{6+10} = .315$ #/hr

" " $O_2 = \frac{3(22.5+13)}{6+10} = 6.65$ SCFH

AVE NIGHT $CO_2 = 3 \times .06 = .18$ #/hr

" " $H_2O = 3 \times .18 = .54$ #/hr

" " $O_2 = 3 \times .63 = 1.89$ SCFH

* NOTE THE DAYTIME H_2O LEVEL SHOULD BE INCREASED TO .52 #/hr TO ACCOUNT FOR 1.1#/MAN DAY SKIN EVAPORATION.

TITLE: ENVIRONMENTAL CONDITIONING LOOP
DESIGN CALCULATIONS
BY: JMC DATE:

DESIGN ADSORBENT BEDS TO BE
DESORBED 1 TIME EVERY 24 HRS

TOTAL CO_2 = 12 # / DAY

EACH BED MUST ADSORB 6 # CO_2

LOOP FLOW – 18 CFM DAYTIME
9 CFM NIGHT

HEAT EXCHANGER (SEE SECTION III):

AT 18 CFM ASSUME VELOCITY = 3.5 '/sec

FLOW AREA REQ'D/SIDE = $\frac{18}{60 \times 3.5}$ = .086 ft^2 = 12.4 in^2

TOTAL AREA ≅ 25 in^2

LENGTH (FOR 170 ATA) = 5.2'

PRESSURE ATA	ρ #/cu ft	C_p BTU/#°F	ΔP " H_2O	ΔT °F	REFRIG BTU/hr
10	.135	.95	2.8	1.6	220
50	.535	1.174	5.7	2.2	1460
90	.935	1.206	9.3	2.4	2950
130	1.335	1.219	12.4	2.6	4600
170	1.735	1.226	15.4	3.0	6900

NIGHT REFRIG REQMT ~ ½

TITLE: ENVIRONMENTAL SYSTEM DESIGN CALCULATIONS
BY: JMC DATE:

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ADSORBER DESIGN (SEE SECTION V):

ADSORBER A - DAYTIME

FLOW 18 CFM, CO_2 ~ .675 #/Hr
H_2O - SATURATED AT 32°F
= 2 grains/cu ft

TIME BEFORE DESORBING:

$$\frac{6}{.675} = 9 \text{ HOURS}$$

∴ ADSORBER B 15 HR ADS., 9 HR DES.

WATER REMOVAL REQ'D

$$CFM \times 60 \times 9 \times \frac{grains}{7000}$$

$$= \frac{18 \times 60 \times 9 \times 2}{7000} = 2.76\ \#$$

ASSUME CAPACITY SILICA GEL IS 15% BY WT

$$\text{SILICA GEL REQ'D} = \frac{2.76}{.15} = 18.5\#$$

ρ = 45 #/cu ft NEED ~ .41 cu ft

CO_2 REMOVAL

TYPE 5A MOLECULAR SIEVE ~ 10% CAP

$$\text{NEED } \frac{6}{.1} = 60\# \text{ SIEVE}$$

TITLE: ENVIRONMENTAL SYSTEM
DESIGN CALCULATIONS
BY: JMC DATE:

ADSORBER DESIGN (CONT):

ASSUME SUPERFICIAL VELOCITY .5'/SEC

AREA = $\frac{18}{(60)(.5)}$ = .6 ft^2

USE SCHED 140 – 12" PIPE - ID = 10.5"
OD = 12.5" AREA = .601 ft^2

SILICA GEL SECTION = $\frac{.41}{.6}$ = .68 ft

MOLECULAR SIEVE SECTION = $\frac{1.2}{.6}$ = 2 ft

OVERALL LENGTH ~ 3½ FT

DESORBING - HEAT TO ~120°F

WT OF SHELL ~ 530#
HEAT CAPACITY ≃ 53 BTU/°F

Q TO HEAT SHELL = 53 (120 - 32)
= 4600 BTU

Q TO HEAP ADSORBENT ≐ .2 (60+18.5)(120-32)
= 1400 BTU

Q TO REMOVE WATER (ASSUME 2500 BTU/# WATER)
= 2500 x 2.76
= 6900 BTU

Q TO REMOVE CO_2 (ASSUME 200 BTU/# CO_2)
= 1200 BTU

Q HEAT LOSS = 1200 BTU

TOTAL HEAT 15,300 BTU

TITLE: ENVIRONMENTAL SYSTEM DESIGN CALCULATIONS
BY: JMC DATE:

DESORPTION (CONT)

TOTAL HEAT REQ'D 15,300 BTU

IF REACTED OVER A 4 HR PERIOD

Would NEED 3,800 BTU/hr ~ 1.2 KW

COOLING TO 32°F

SHELL	4600 BTU	
ADSORBENT	1400 BTU	
	6000 BTU	TOTAL

GAS LOSS ON BLOWDOWN APPROX 50% OF VOLUME OR ~.8 cu FT

USE DAVIDSON GRADE 05 SILICA GEL
& LINDE TYPE 5A SEIVE 1/16" PELLETS

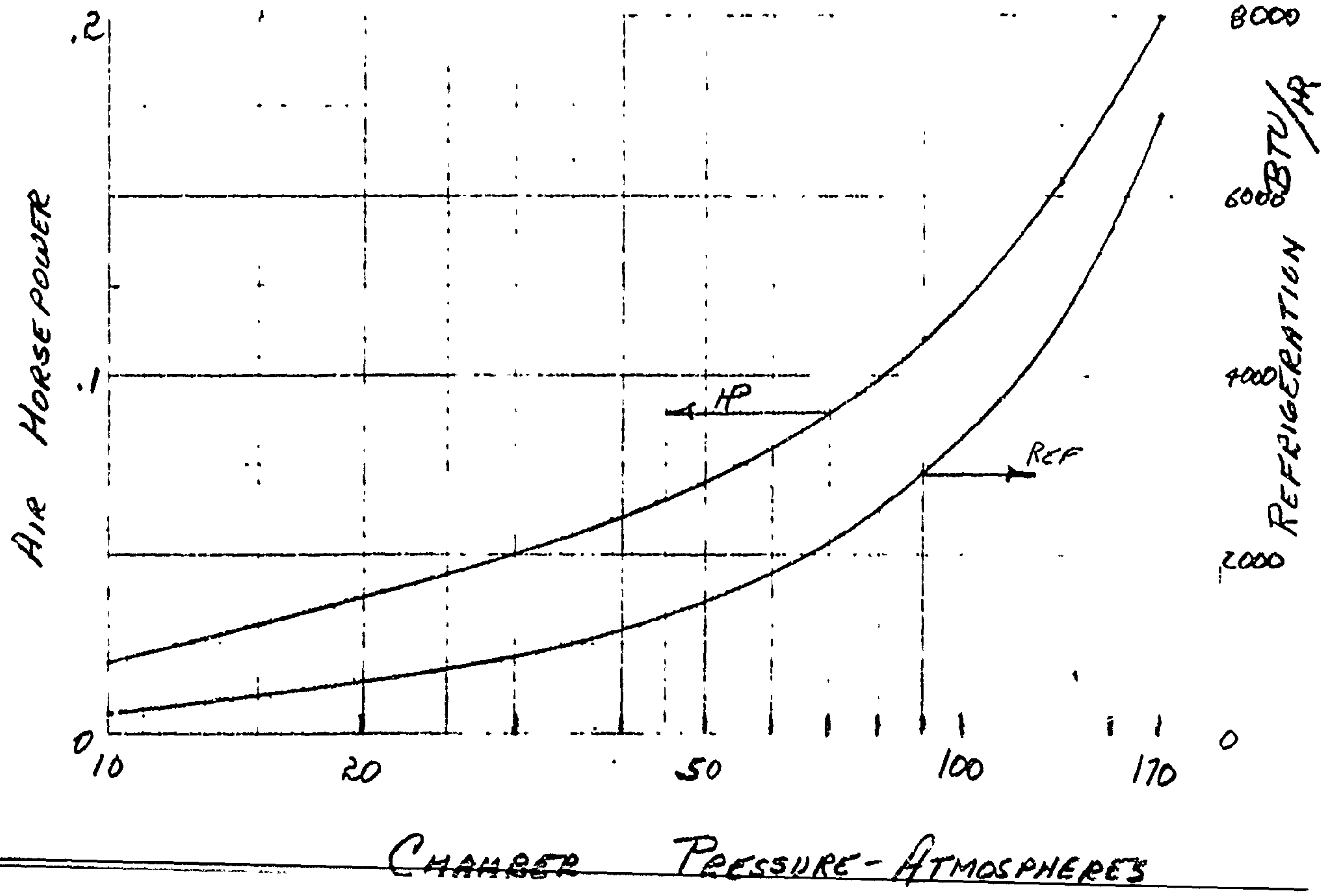
PRESSURE DROP THROUGH BED

P ATMOS	ΔP "H_2O	ΔP PIPING (~10') "H_2O
10	2.3	2.2
50	10	8.7
90	15	15.2
130	21	21.5
170	28	28

TITLE: ENVIRONMENTAL SYSTEM DESIGN CALCULATIONS
BY: JMC DATE:

DESIGN SUMMARY - 18 CFM

PRESSURE ATMOS	TOTAL ΔP "H_2O	AIR HP (IDEAL)	REFRIG BTU/hr
10	7.3	.02	220
50	24.4	.07	1460
90	39.5	.11	2950
130	54.9	.154	4600
170	71.4	.2	6900



TITLE: PASS THRU LOCK MODULE DESIGN CALCULATIONS
BY: J M C DATE:

JOHN M. CANTY, P. E.
ENGINEERING CONSULTANT
117 CORNWALL AVENUE
TONAWANDA, NEW YORK 14150
(716) 832-6554

SEE FIG VI-3

PASS THRU LOCK MODULE - CHANGE EVERY ½ DAY - 6# CO_2 (SEE PAGES VI 8 & 9)

MAXIMUM WATER REMOVAL - MOISTURE FROM OCCUPANTS DURING DAY .51 #/hr or for 9 hrs (see P VI-10) 4.6#

MOISTURE FROM CO_2 REACTION $1\ell CO_2 \rightarrow 1\ell H_2O$

$$\frac{M_{H_2O}}{M_{CO_2}} \times W_{CO_2} = \frac{18}{44} \times 6 = 2.5^{\#}$$

TOTAL WATER 7.1#

BARALYME REQ'D $\frac{6}{.2} = 30^{\#}$ ~ .47 cu ft

MODULE DIAMETER 8"

LENGTH OF BED = $\frac{.47}{\frac{\pi}{4}\left(\frac{8}{12}\right)^2}$ = $\underline{\underline{1.35 ft}}$

TOTAL MODULE LENGTH 2.35' (28")

Vol SILICA GEL = $\frac{\pi}{4}\left(\frac{8}{12}\right)^2$ = .35 cu ft

Wt = 16#

This will remove about .35X16 = $\underline{5.5^{\#} H_2O}$

PART OF THE GAS MUST BYPASS SILICA GEL