WADD TECHNICAL REPORT 60-622

PROPELLANT-ATMOSPHERE SYSTEM STUDY

NEW DEVICES LABORATORIES

TAPCO GROUP

THOMPSON RAMO WOOLDRIDGE INC.

CONTRACT MONITOR: ROBERT W. ROUNDY
CONTRACT No. AF 33(616)-6514
PROJECT No. 6373
TASK No. 63124

MARCH 1961

LIFE SUPPORT SYSTEMS LABORATORY
AEROSPACE MEDICAL LABORATORY
WRIGHT AIR DEVELOPMENT DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

800 - December 1961 - 12-433 & 434

FOREWORD

This study was initiated by the Life Support Systems Laboratory, Aerospace Medical Laboratory, under Contract No. AF 33(616)-6514, Project No. 6373, "Equipment for Life Support in Aerospace," Task No. 63124, "Integrated Systems of Life Supporting Equipment." Mr. Allen Schwartz and Mr. Robert Roundy, Sustenance Branch, Life Support Systems Laboratory, served as contract monitors. This report, designated Thompson Ramo Wooldridge Inc. Report No. ER-4257, was compiled to summarize the work conducted by the New Devices Laboratories, Cleveland, Ohio, between May 1959 and May 1960. The work was performed under the direction of Dr. N. Fatica.

ABSTRACT

Two broad aspects of using chemical energy to provide metabolic oxygen in a manned space capsule were studied: man's ecological requirements and supply of auxiliary power. The studies were restricted to chemicals used in propulsion systems with emphasis on by-products useful to man.

A survey of methods for meeting environmental requirements included (a) evaluation of passive temperature control in terms of capsule size, shape, surface emissivity, orbital altitude, orientation, and internally generated power, and (b) evaluation of weight and energy requirements for supplying oxygen, dehumidifying, and removing CO_2 in the cabin.

The best of 40 fuels and 35 oxidizers were screened for other factors: weight of the containers, general methods for converting the energy to electric power, mechanical prime movers (their efficiencies, cycle configurations, weight, specific fuel consumption), thermionic, thermoelectric, and electrochemical conversions. The unique adaptability of the cryogenic hydrogen-oxygen fuel system was demonstrated. This system combined with a hydroxy fuel cell was used in developing a prototype designed to accommodate one man for 3 days and to supply 1 kilowatt of electric power. The prototype included optimization studies of the cryogenic storage system, an air conditioning system, and a fuel cell power system.

PUBLICATION REVIEW

Wayne H. McCandless
WAYNE H. McCANDLESS
Chief, Life Support Systems Laboratory
Aerospace Medical Laboratory

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

1.0 INTRODUCTION

The possibilities of various chemical systems were examined during the Propellant-Atmosphere System Study, AF 33(616)-6514, to find a system meeting both operating power and occupant requirements for a manned space capsule on a mission of several days. Power, oxygen, and water supplies, temperature control, and the removal of carbon dioxide, water vapor, and other undesirable gases within the sealed cabin were considered. After completion of the survey, we critically examined the problem areas in a design study of a well-integrated prototype system of minimum weight and maximum reliability.

The preliminary survey indicated that a system using cryogenic hydrogen and oxygen as the primary chemical source could best meet the objectives. Accordingly, we proceeded with the design of such a system, with a mission duration objective of up to three days. WADD expressed preference for a portable or semiportable unit. Based on preliminary analyses, a one-kilowatt power unit and environmental system weighing about 200 pounds was selected as a reasonable design objective for the three-day mission.

To provide these requirements, we evaluated the occupant's ecological needs and tolerances in terms of environmental parameters such as temperature, oxygen supply, carbon dioxide concentration, relative humidity, and water supply (Section 2.0). We considered the environmental system design on the following bases:

1. Metabolic rate of 500 Btu/hour.
2. Oxygen consumption of 2 pounds/day, with cabin air maintained at practically 100% oxygen at 5 psia pressure.
3. Carbon dioxide evolution of 2.2 pounds/day, with the partial pressure not exceeding 4 millimeters mercury at any time.
4. Moisture evolution at the rate of 2.5 pounds/day, with the cabin air maintained at 50 ± 10% relative humidity.
5. Minimum water requirements of 6 pounds/day.
6. Temperature of $70^{\circ}F \pm 5^{\circ}F$.

Various means and methods for supplying environmental requirements are surveyed in Section 3.0. Emphasis was confined to methods applicable to mission durations of one day to three weeks. In compliance with the statement of the problem, if energy were required for environmental control, the source was restricted to chemical energy carried on board; solar and nuclear energy were not considered for this capsule. These restrictions ruled out various environmental processes, including regeneration of oxygen from body wastes (e.g., water and carbon dioxide).

The study of temperature control of the space capsule was also restricted, because the magnitude of this problem is so dependent on the system aspects of the mission and capsule design. Internally generated heat produced at rates less than 3 to 4 kilowatts in a 6-1/2-foot diameter spherical capsule can be dissipated from the capsule wall in orbit under suitable conditions. This is more than the internally generated power in the prototype design, so no attempt was made in the design to supply cabin cooling other than that available from the cryogenic fluids.

While the passive method of temperature control may be adequate in orbit, it is probably unrealistic when considering re-entry heating. In either case, if additional cooling is required, a refrigerating unit may be added to the designed prototype without any significant alterations in the hardware and without any more of a weight penalty than if the unit had been considered as part of the original layout. (It may be assumed that part of the one-kilowatt electrical load supplied is for a refrigeration unit.)

In addition to the problem of thermal control, Section 3.0 includes a comprehensive and critical survey of the methods used to supply oxygen and remove carbon dioxide. The survey relied heavily on the wealth of naval experience gained through control of gases in submarines during the last 30 years.

Dehumidification was considered as a matter of comfort. The problem is handled with a minimum weight penalty through heat exchange with cryogenics.

Because of the importance of the power unit from the weight standpoint, an exhaustive preliminary survey (Section 4.0) of all known chemical fuels and oxidants was made to select those with the highest available energy which were still compatible with the occupant's requirements. The most promising combinations are detailed in Section 5.0.

To estimate system weights, we conducted subsystem studies of cryogenic containers, gas expansion engine efficiencies, and cycle configurations, and of fuel cells because of their high efficiency and applicability to this particular investigation. From the viewpoint of minimum weight, cryogenic hydrogen and oxygen combined in the hydroxy fuel cell is definitely superior to any other system considered. It is unique in that it not only has a high theoretical energy value per pound, but also is adaptable to electrochemical conversion with efficiencies much higher than could be obtained from present gas expander engines and cycles. When compared with potentially more energetic chemical energy sources, which rely on heat engine cycles with their lower efficiency, hydrogen and oxygen combined in the fuel cell result in system weights comparable to or better than any chemical-heat engine combination known. Thus, the hydrogen-oxygen system, based on energy considerations alone, is the logical fuel source. In addition, and important in this case, it is uniquely adaptable to man's requirements, not only serving as a ready source of pure oxygen, but also supplying pure water easily and simply.

If the use ratio of the combined gases exceeds 0.6 pound /hour, the system can dehumidify the cabin atmosphere. At higher rates, it may also be sufficient to cool the cabin. Excess water available at the higher power levels can be condensed with a small weight penalty and the condensate used for transpirational cooling on re-entry.

Weight was the major factor considered in the preliminary system analysis. Systems generating hydrogen from chemicals to improve both the weight ratio and the extraction of power per pound of chemicals were considered and are summarized in Section 5.0, but their prospects do not appear very attractive.

The prototype design is included in Section 6.0, along with a presentation of many of the engineering calculations, the basis for the selection of various components of the system, and the evolution of the designs. We do not intend that the design concepts be immediately transformed to hardware without filling in many important engineering details. The design is primarily illustrative.

Having appraised future prospects of chemical systems, we have little doubt that cryogenic hydrogen-oxygen systems will find a place in manned space missions of limited duration, especially if one considers the ability of this system to supply electric and reaction power for the vehicle. Man's ecological requirements can be easily satisfied with relatively small weight penalty, so power system requirements are of prime importance. Proven designs and adequate controls will minimize explosion hazards.

Whether conversion to electrical power is via the hydroxy fuel cell or mechanical engines will depend on the future rate of progress in these areas. Presently, inherently high efficiency makes the fuel cell preferred for applications where the weight of the fuel is predominant.

2.0 MAN'S PHYSIOLOGICAL REQUIREMENTS

The basic requirements of a human in a hermetically sealed space cabin include: sufficient quantities of oxygen, water, and food to sustain metabolic processes; conducive environmental conditions of pressure, temperature, and humidity; and protection from excessive quantities of toxic gases, harmful radiation, and high acceleration. With the exception of radiation and acceleration, these requirements may be considered in terms of five major independent variables: (1) size, (2) degree of activity, (3) type of diet, (4) environmental temperature, and (5) relative humidity. The calorific food requirements, for example, depend on the size and degree of activity. These food requirements, when combined with the prerequisites for maintaining a balanced diet for optimum body function, determine the oxygen requirements, and the heat and carbon dioxide involved. The water balance, which considers both the water requirements and fluid wastes (perspiration, expiration, urine, and fecal matter), is dependent not only on size and degree of activity but also on the environmental temperature and relative humidity.

In this section the above requirements are established in terms of the expected metabolic rate of the occupant, a balanced diet, the temperature, and relative humidity. This is followed by considerations of the tolerance limits to oxygen and CO_2 concentrations, temperature, and relative humidity. Methods for meeting these requirements are treated in Section 3.0.

2.1 OCCUPANT REQUIREMENTS

2.1.1 Expected Metabolic Rate

The metabolic rate, a function of both the size and activity of the occupant, is one of the more important parameters to be considered in establishing the occupant requirements. The size of the man determines a base metabolic rate (BMR). All degrees of activity can be expressed in percentages of the BMR.

The BMR for adult males between 20 and 40 years of age was shown by Aub and DuBois (ref. 1) to be about 39.5 kilocalories per square meter of body surface per hour. They also expressed the body surface in terms of the weight and height of the man as follows:

$$A = 71.84(10)^{-4} W^{0.425} H^{0.725}$$

where A = Surface area in square meters
W = Weight in kilograms
H = Height in centimeters

This expression is shown in graphic form in Figure 2-1. Variations in the BMR may be caused by various factors such as mental stress, illness, and temperature, but the most important factor is the degree of activity of the human body. Numerous tabulations of metabolic rate for various activities have been made available by physiologists. For

CHART FOR DETERMINING SURFACE AREA OF MAN IN SQUARE METERS FROM WEIGHT IN KILOGRAMS (WT.) AND HEIGHT IN CENTIMETERS (HT.) ACCORDING TO THE FORMULA: AREA (SQ. M) = $WT.^{0.425} \times HT.^{0.725} \times 71.84 \times 10^{-4}$

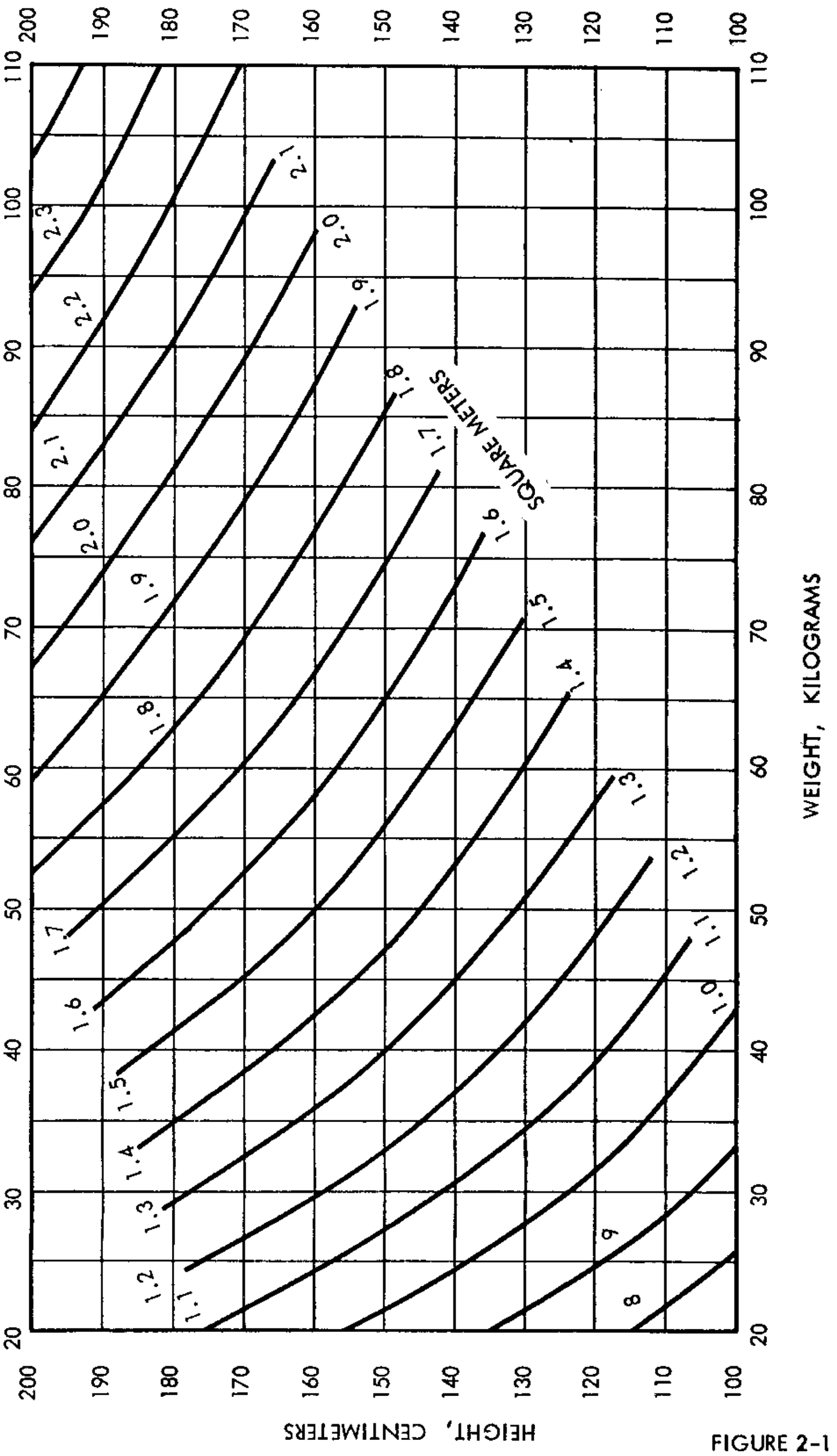


FIGURE 2-1

example, Appendix I gives the hourly expenditure of kilocalories of an average man (154 pounds and 5 feet 8 inches) as summarized by Mary Swartz Rose (ref. 2). With such information, a schedule of activity may be worked out for the average man in a sealed space cabin and his daily energy expenditure computed. This has already been done by E. B. Konecci (ref. 3). For convenience this schedule is reproduced in Table 2-1. The total energy expenditure thus arrived at is 3000 kilocalories per day. This is a commonly accepted figure appearing frequently in the literature (ref. 3, 4, 5, 6, 7).

TABLE 2-1

ESTIMATED DAILY ENERGY EXPENDITURE
FOR AN AVERAGE MAN IN A SEALED CABIN

Condition	Duration	Kilocalories Per Hour	Kilocalories Per Day
Sleep	8 hr	65	520
Light work	8 hr	150	1200
Rest, sitting	5 hr	100	500
Rest, lying	1 hr	80	80
Light exercise	1 hr	200	200
Heavy exercise, or work	1 hr	500	500
			3000 = 12,000 Btu

2.1.2 Diet Requirements, Oxygen Requirements, and Carbon Dioxide Evolved

A hypothetical but balanced diet which will supply the above metabolic requirements is given in reference 6 as follows:

450 grams carbohydrates
100 grams proteins
75 grams fat
625 grams

This diet has been analyzed from a chemical and thermo viewpoint in Appendix II. The analysis yielded the following results:

2816 kilocalories metabolic rate
1.84 pounds O_2 required
2.26 pounds CO_2 formed
0.84 pound water formed
Respiratory Quotient (RQ) = 0.89 = Vol CO_2 produced/Vol O_2 consumed

In practice this diet must be supplemented by approximately 25 grams of mineral salts and vitamins, and by some palatable substances and also ballast substances of the cellulose variety necessary for normal peristalsis (contraction) of the bowels. This may amount to an additional 150 grams, giving an overall total for dry food of about 800 grams or 1.76 pounds per man per day.

The preceding analysis, based on the theoretical diet mentioned above, agrees fairly well with the metabolic data on man given in reference 4. The metabolic data from reference 4 was also used in references 7 and 8 and for convenience is summarized in Table 2-2.

TABLE 2-2

METABOLIC DATA ON MAN

Substance		Input, Lb/Day	Output, Lb/Day		
Oxygen		2.0	Carbon Dioxide		2.2
			Fecal solid		0.2
Food concentrates		1.5			
Water*		4.8	Vapor		1.9
In Foods	(2.6)		Sweat	(1.1)	
In Drinks	(2.2)		Expired air	(0.8)	
			Liquid		3.6
			Urine	(3.3)	
			Fecal water	(0.3)	
Heat Output 12,000 Btu/Day					
TOTALS		8.3**			7.9

* Water balance shows 5.5 pounds H_2O output and 4.8 pounds input, leaving 0.7 pound per day formed by food metabolism. This may be compared with the 0.84 pound computed in Appendix II.

** Growth and matter losses account for higher intake.

The most significant point to be derived from the simplified analysis presented in Appendix II, however, is that the oxygen consumption and CO_2 evolved can be estimated from the metabolic rate and the type of diet specified. This latter factor is often characterized by the respiratory quotient, RQ. There is a general agreement among various authors on the oxygen consumption rate of 2 pounds/day for a metabolic rate of 3000 kilocalories/day or 500 Btu/hour. The issue is not so clear for the evolution of carbon dioxide, the main reason being that different sources do not consider the same diet. Depending on the relative ratios between carbohydrates, proteins, and fats our calculations summarized in Appendix II indicate that an RQ of 0.7 to 1.0 may be possible. This in turn leads to 1.9 to 2.7 pounds CO_2 evolved per day.

A respiratory quotient of about 0.8 seems to be the most often quoted. This is equivalent to 2.2 pounds CO_2 which is in close agreement with the computed value. This value is used as the basis for environmental design in this study.

2.1.3 Water Balance

Establishing a reliable water balance is important because it determines not only the water that must be supplied to the occupant but also the load to be applied to the dehumidifier. This is a quantity which, like carbon dioxide, depends on the metabolic rate and the diet type. In addition to the water vapor expired through the lungs from the oxidation of foods, a much larger quantity is involved in maintaining normal body temperatures by the evaporative cooling mechanism built into the perspiration system. Table 2-3 (ref. 9) shows the normal avenues of heat loss from an average man with a 3000-kilocalorie metabolic rate at normal temperature (68°to 70°F).

TABLE 2-3

NORMAL AVENUES OF HEAT LOSS FROM THE HUMAN BODY
BY AN AVERAGE MAN AT NORMAL TEMPERATURE

Method	Approximate Percent of Total Loss	Approximate Calories Lost Per Day
Radiation and conduction	73.0	2200
Evaporation from skin	14.5	450
Evaporation in lungs	7.0	200
Warming of air in lungs	3.5	100
Urine and feces	2.0	50
	100.0	3000

Even during light activity at ordinary room temperatures, evaporation accounts for 21.5% of the total heat loss from the body: 14.5% by sensible evaporation from the surface of the skin and 7% by insensible evaporation from the inner surface of the lungs. This amounts to 650 kilocalories per day. Since the latent heat of evaporation of water at room temperature is approximately 0.6 kilocalorie per gram, the amount of heat lost by evaporation for this example would necessitate the removal of 650/0.6 = 1080 grams of water from the body. This is equivalent to about 2.5 pounds of water per day that is evaporated from the body under normal circumstances of light activity and room temperature. This estimate is also substantiated in references 1, 2, 4, 9 and is therefore used as the basis for our design studies. The quantity, however, is very sensitive to the degree of activity of the man as well as to the ambient temperature. This is graphically illustrated in Figure 2-2 (ref. 10).

The amount of water evaporated increases sharply as the ambient temperature exceeds 70°F. Above 98°to 100°F the evaporative heat loss must be at least as large as the metabolic rate since this is the only means available for heat dissipation by the body above these temperatures. For a metabolic rate of 3000 kilocalories/day (500 Btu/hour) the minimum amount of water lost by evaporation above these temperatures is at least 12.7 pounds/day. The actual amount of water lost by the body under such conditions may be considerably larger than

EVAPORATIVE HEAT AND MOISTURE LOSS FROM THE HUMAN BODY IN RELATION TO DRY-BULB TEMPERATURE FOR STILL AIR CONDITIONS

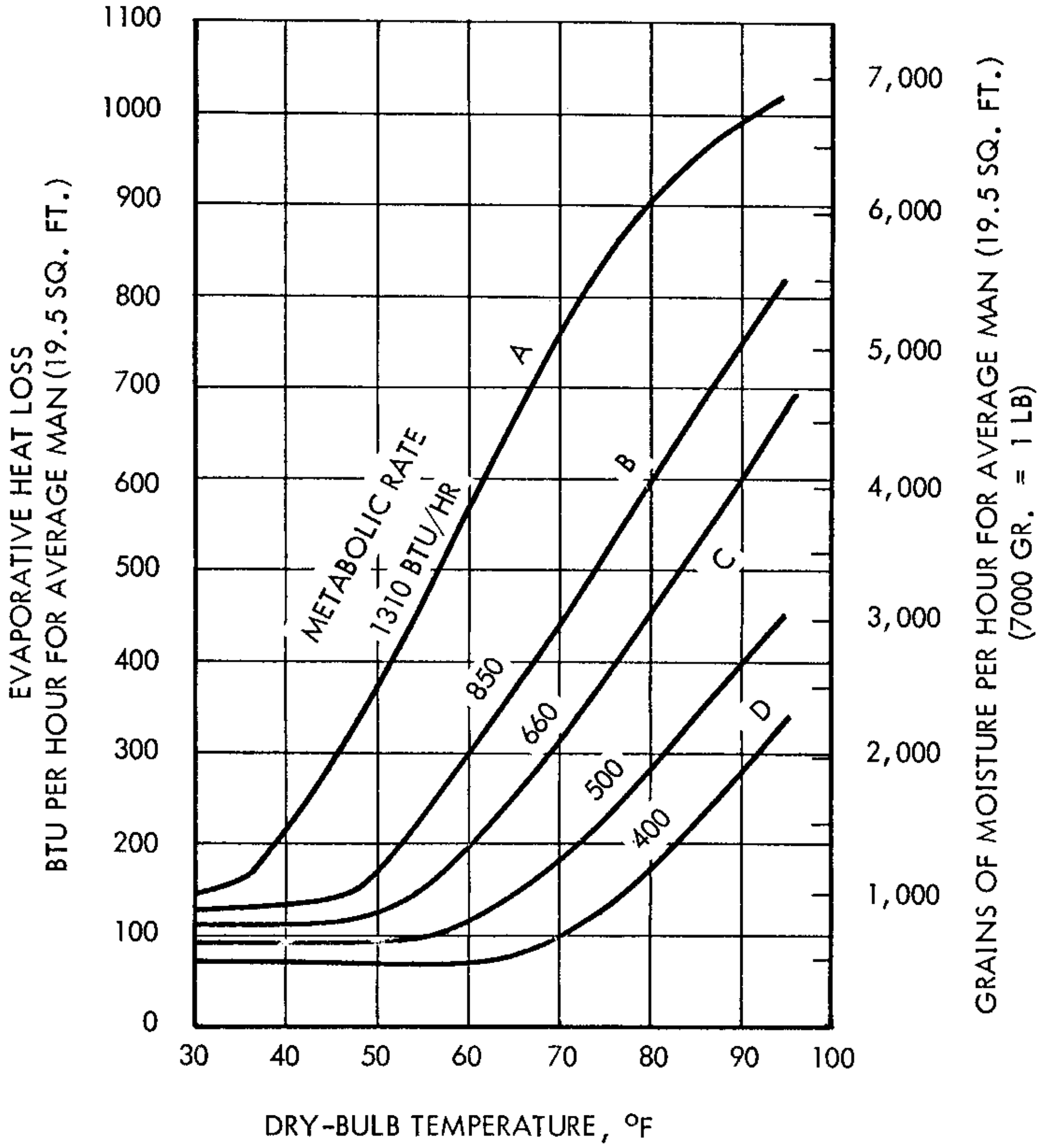


FIGURE 2-2

this since much water secreted by the sweat glands may run off as such without performing its intended function.

The importance of keeping the environmental temperature as low as consistent with the occupant's comfort is obvious. Failure to maintain moderate temperatures will result in at least double penalty in the sense that not only will the dehumidifier load be increased but, at the same time, the additional water that must be supplied to the man to maintain his water balance will impose additional requirements on the water supply. [Approximately two-thirds of the total body weight is water. A reduction of 20% in body water is usually fatal (ref. 2).]

Table 2-2 shows that 4.8 pounds of water will be required daily for occupant consumption. About half of this is supplied as the natural water content of solid foods while the remainder is consumed in the form of liquids. These estimates are also substantiated in reference 2. The latter fluids can almost certainly be derived from juice concentrates and recovered water. There is a good possibility that about another pound can be cut from the solid foods by considering dehydrated foods. Thus, it appears that a maximum of about 3.5 pounds of water daily will have to be supplied for human consumption. In addition, a minimum of 2.5 pounds/day is considered necessary for personal hygiene, bringing the total minimum water requirements up to 6 pounds/day. This is the basis considered for design.

2.2 TOLERANCE

Although the daily oxygen requirements of the occupant have been specified, nothing has been said concerning permissible concentrations in the environmental atmosphere. Concentrations above or below an optimum are dangerous. Carbon dioxide also has an upper limit of concentration in the environmental atmosphere; a lower limit becomes a practical necessity if one considers the size of the equipment involved to remove all of it. Finally, one must consider the zones of optimum comfort as related to temperature and relative humidity. In the following paragraphs not only are the optimum quantities of the above variables specified but, in addition, the endurance of the human being to extreme conditions are considered to assess the dangers of possible malfunctioning of the required components.

2.2.1 Oxygen

The physiological limit for the partial pressure of oxygen in the atmosphere is a function of the percentage of oxygen saturation obtained in the arterial blood supply (e.g., at a partial pressure of 64.3 millimeters-mercury the oxygen saturation of the arterial blood is 65% and useful consciousness is limited to about 10 minutes with death occurring in about 15 to 30 minutes (ref. 15).

The symptoms of anoxemia occurring at partial pressures of less than 90 millimeters mercury are:

a. Euphoria, resulting in overconfidence and disregard for sensory perception
b. Impaired judgment

c. Fine muscular incoordination
d. Sleepiness
e. Headache
f. Dizziness
g. Impairment of vision
h. Gradual increase in heart rate and breathing

On the other end of the scale, an upper physiological limit for the partial pressure of oxygen has been set at 425 millimeters mercury (refs. 3, 8, 15). Exceeding this limit will expose the human passenger to the effects of hyperoxia:

a. Inflammation of the lungs
b. Respiratory disturbances
c. Coughing
d. Gasping
e. Pulmonary congestion
f. Various heart symptoms
g. Numbness of the fingers and toes
h. Nausea
i. Irritation of the eyes
j. Virtual blindness
k. Loss of consciousness and convulsions

Time tolerances of a human being to various oxygen partial pressures are illustrated in Figure 2-3 (ref. 8). On the basis of the foregoing information a lower physiological limit of the partial pressure of oxygen in the atmosphere of the sealed space cabin has been set at 100 millimeters mercury (ref. 3, 17). The normal environment for the Mercury capsule has been set at 258 millimeters mercury (5 psia) with 100% oxygen (ref. 18). In spite of the fears expressed by some writers on the increased dangers of a pure oxygen atmosphere on inflammability, we feel that the additional risks involved are commensurate with other dangers faced in a flight of this type, and that the additional weight required to carry a diluent are not justified. We see no reason, therefore, for deviating from employing the same conditions being contemplated for Project Mercury, namely 100% oxygen at 5 psia.

2.2.2 Carbon Dioxide

No beneficial effects from small quantities of carbon dioxide inhaled by adults under normal conditions are known. The effects of partial pressures of CO_2 above 15 to 20 millimeters mercury are:

a. A noticeable increase in the breathing rate
b. Distension of the air sacs of the lungs
c. Impairment of the normal gas exchange in the lungs

Partial pressures of CO_2 above 35 millimeters mercury can be tolerated only a few minutes as shown in Figure 2-4 (ref. 15). The Mercury capsule will maintain a partial pressure

HUMAN TOLERANCES: TIME VS OXYGEN PARTIAL PRESSURE

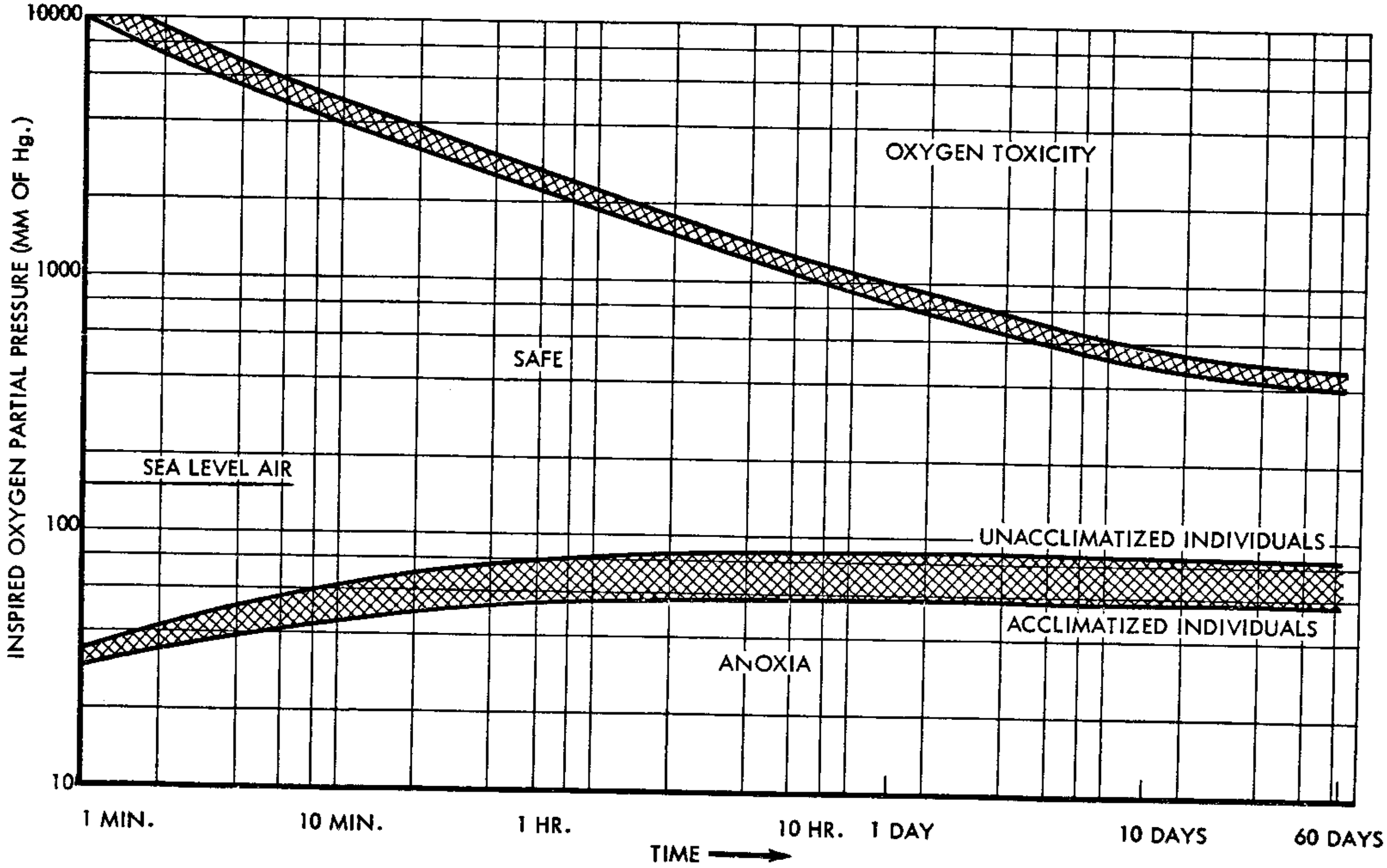
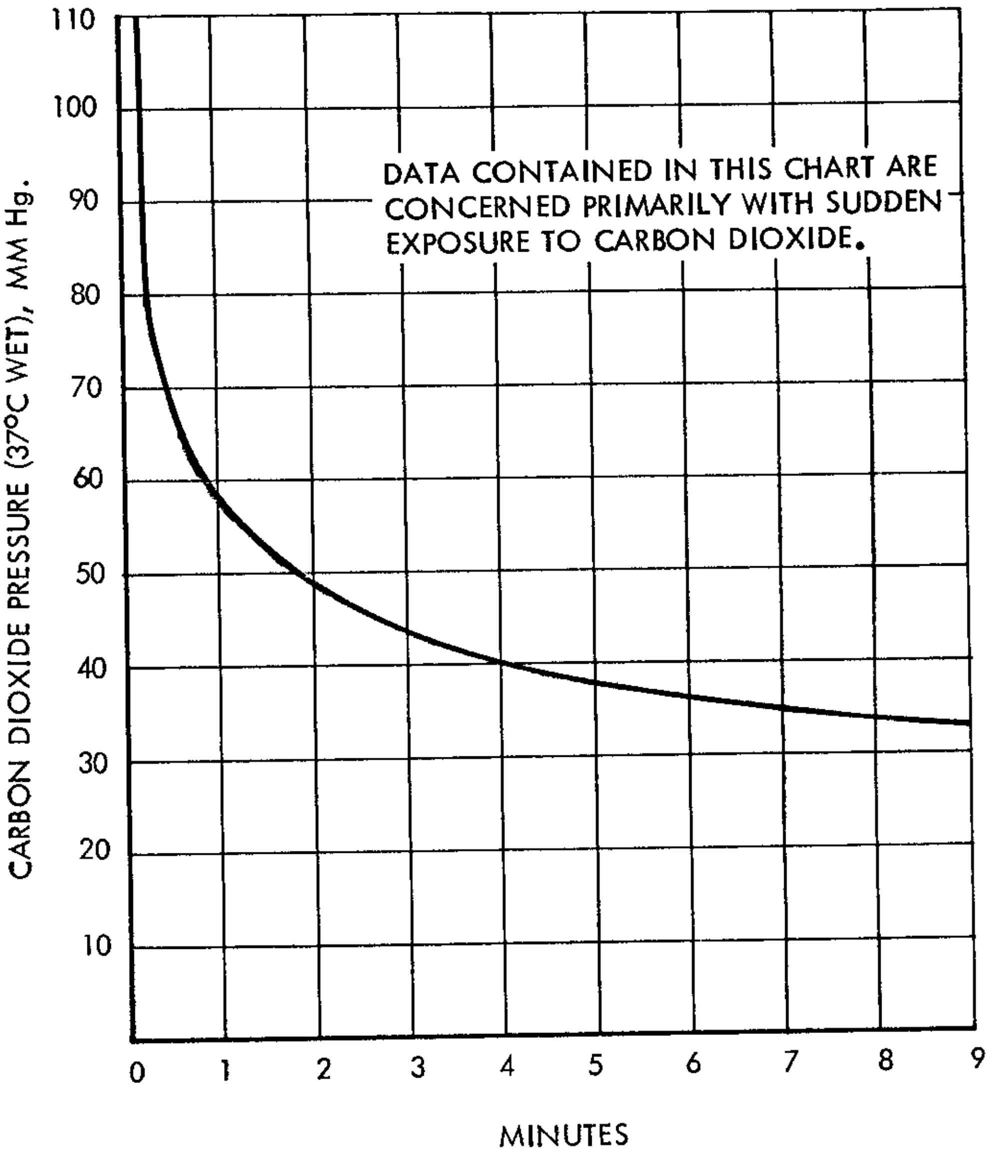


FIGURE 2-3

CARBON DIOXIDE TOLERANCE



DATA CONTAINED IN THIS CHART ARE CONCERNED PRIMARILY WITH SUDDEN EXPOSURE TO CARBON DIOXIDE.

FIGURE 2-4

equal to or less than 4 millimeters mercury (ref. 18). This concentration maximum is also being adopted in this study.

2.2.3 Temperature and Relative Humidity

The region of comfort relative to temperature and humidity in still air is illustrated in the ASHVE comfort chart (ref. 10) reproduced in Figure 2-5. This chart, derived from experiments with a large number of people, shows the relationship between the ambient temperature, relative humidity (or wet bulb temperature) versus the percentage of people feeling comfortable at each set of conditions. Due to the ability of the human to acclimate himself to some extent, the value differs for the various seasons of the year. Thus, during the summer the greatest percentage of people are comfortable at an effective temperature of 71°F. This means that the occupant will experience the same sensation of comfort for any combination of ambient temperature and relative humidity that lies on the 71°F effective temperature line. During the winter the effective temperature is about 68°F. Assuming an average effective temperature of 70°F for both summer and winter, Figure 2-5 shows that 70°F at 100% humidity is equivalent to 81°F at 10% humidity. Thus one can tolerate higher temperatures at lower humidities. This point is illustrated more effectively perhaps in Figure 2-6 (ref. 8) which, in addition to showing trends similar to the ASHVE comfort chart, also indicates the human tolerance to various combinations of temperature and humidity.

It is pertinent at this point to examine the consequences of inadequate heat transfer between the occupant and his surroundings. The basic heat balance between the occupant and his environment may be described by the following equation:

$$W\Delta T_B = M - k_1 A(T_B - T_S) - k_2 A(T_B{}^4 - T_S{}^4) - k_3 A p_{TB} \left(\frac{100 - RH}{100}\right)$$

where W	is the weight of the man
ΔT_B	is his body temperature rise over the period being considered
M	is his metabolic rate
A	is his body surface area
T_B	is his body temperature
T_S	is the temperature of the surroundings
p_{TB}	is the vapor pressure of perspiration at body temperature
RH	is the relative humidity
k_1, k_2, k_3	are proportionality constants for the convective heat transfer, radiative heat transfer, and evaporative heat transfer, respectively.

M is always positive. When the temperature of the surroundings equals or exceeds the body temperature, the only mechanisms for balancing the metabolic heat are evaporation or heat storage. If, in addition, the relative humidity reaches 100%, all normal avenues of escape of body heat are blocked so that $M = W\Delta T_B$. Based on a body specific heat of 0.23 (ref. 1), it would require 58 kilocalories to raise the body temperature of a 70 kilogram mass 1°C. Assuming the height of the man to be 175 centimeters, his body

A.S.H.V.E. COMFORT CHART FOR STILL AIR

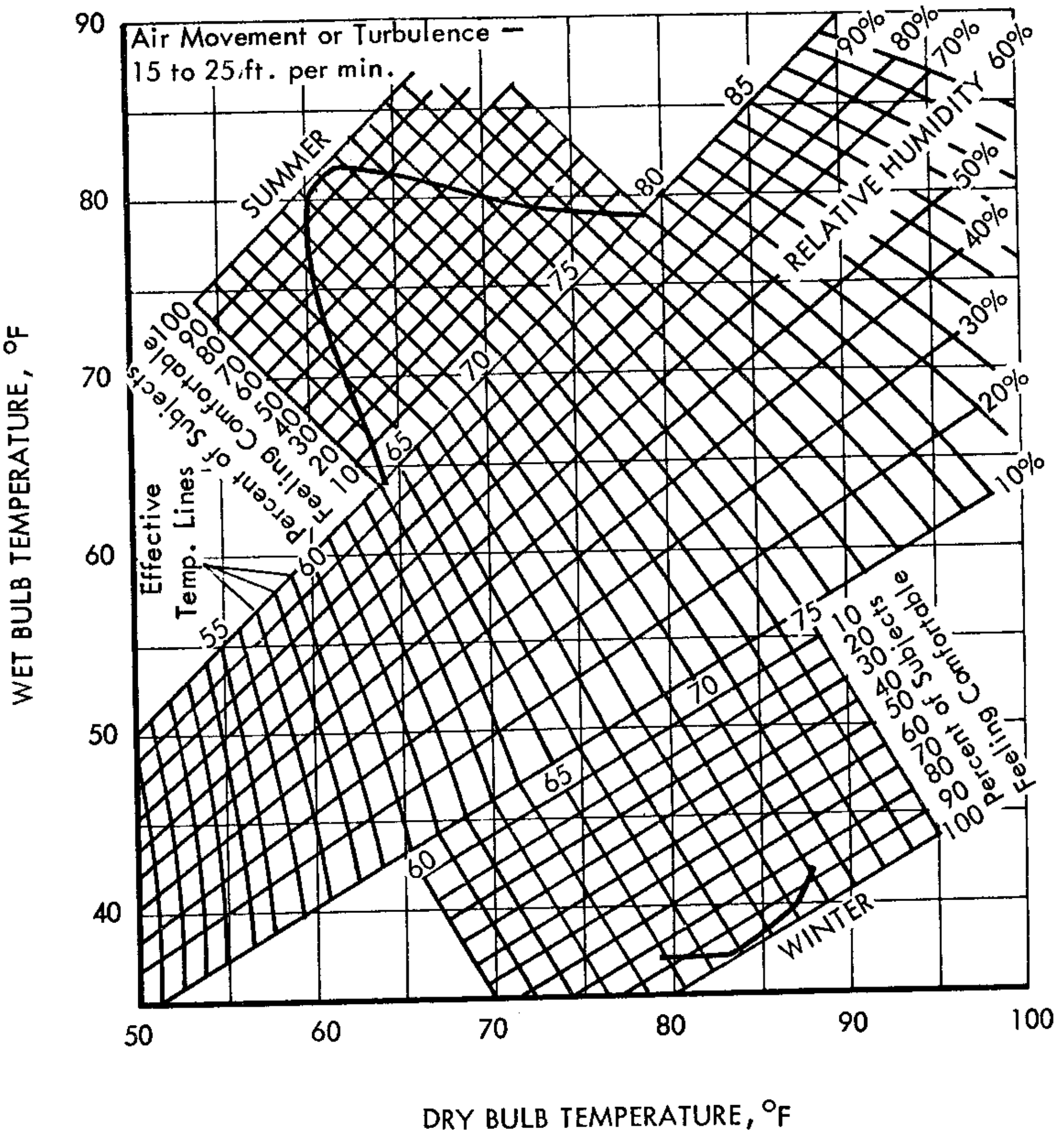


FIGURE 2-5

APPROXIMATE HUMAN TOLERANCES: TIME, TEMPERATURE, RELATIVE HUMIDITY (OPTIMUM CLOTHING)

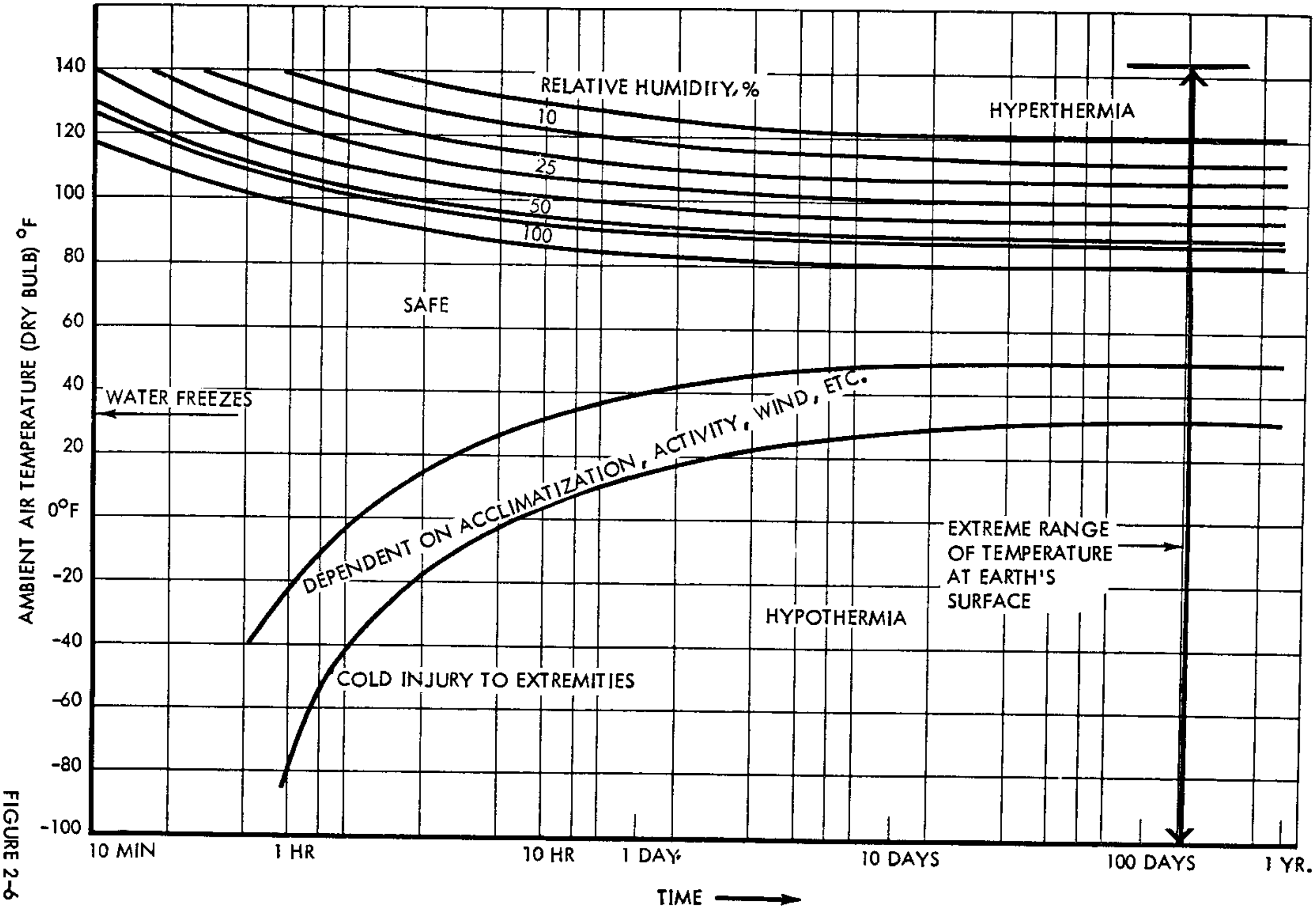


FIGURE 2-6

surface area would be 1.85 square meters (see Section 2.1.1) and his corresponding basal metabolism would be 1.85 (39.5) = 71 kilocalories/hour. Thus it would require less than 1 hour to raise the body temperature 1°C; in fact it would take less than four hours to raise the body temperature of even an unconscious person from 98.6°F to the critically high level of 106°F (T = 41°C).

2.2.4 Other Tolerances

Two other major areas that have manifested themselves in manned space capsules are dynamic forces (acceleration, deceleration) and cosmic radiation tolerances. Considerable information is available in these fields, but since the solution to these problems is outside the scope of the environmental power plant system, they will not be considered further in this study.

2.3 CONCLUSIONS

On the basis of the foregoing considerations, the following average occupant requirements have been selected:

1. Metabolic rate: 500 Btu/hour.
2. Oxygen consumption: 2 pounds/day; 5 psia pressure, 100% O_2.
3. Carbon dioxide evolved: 2.2 pounds/day; 4 millimeters mercury pressure to be maintained.
4. Water vapor evolved: 2.5 pounds/day; 50% ± 10% relative humidity to be maintained.
5. Water requirements: 6 pounds/day.
6. Temperature: 70°F ± 5°F.

Methods for meeting these requirements are evaluated in the following sections.

3.0 ENVIRONMENTAL SYSTEM SURVEY

This section surveys and evaluates various means available for meeting environmental requirements in a manned space capsule. Temperature control, oxygen supply, carbon dioxide removal, water vapor removal, water supply, and noxious odor removal are discussed.

3.1 TEMPERATURE CONTROL

The goal of temperature control of the space capsule is to keep the occupant at a temperature of about 70°F at all times. The capsule will receive energy from the sun and earth. In addition, heat may be generated internally by chemical processes related to environmental control, human cell activity, and power-generation and power-consuming equipment. Radiation and expulsion of mass from the capsule are the only general methods for dissipation of heat into space. The latter method is generally undesirable as it involves weight penalties. Thus, radiation at temperature representing a balance between input and output energy flow rates is the primary method for temperature control.

Factors involved in temperature control may be placed in two categories: (1) those related to the physical aspects of capsule design (i.e., size, shape, mass, capsule wall construction details, and surface emissivity characteristics), and (2) those related to the operational requirements (i.e., orbital altitude, eccentricity, orientation with respect to the earth, attitude of the orbital plane with respect to the plane of the ecliptic, mission duration, power level, re-entry program). Because the temperature at any point within the capsule may vary with time, depending on the orbit chosen, the above parameters must be completely specified before a complete and thorough study of the temperature problem can be made. In this study the power range is too broad and the factors governing capsule design and internal components are too nebulous to permit selection of a method of temperature control. The principal objective of our study of the temperature problem was to determine the maximum heat load that can be removed from the environmental atmosphere without use of a refrigeration system with its attendant weight penalties.

Maintaining internal temperatures at reasonable levels in the presence of appreciable heat release on board is the main difficulty anticipated in controlling temperature while the capsule is in orbit. (Internal temperatures of approximately 70°F have been observed in satellites in orbit when only a few watts of heat are generated internally.)

The maximum heat load that can be transmitted from the environmental atmosphere without use of a refrigeration system can be determined most conveniently by considering the outer skin temperature as the pivotal point in calculations of heat removal using a monotonic temperature gradient between the cabin air and outer space. Then heat input to the outer surface equals the rate of radiant heat transfer into space, Q.

Heat input to the surface is the sum of the heat generated in the capusle, W, plus that absorbed from direct solar radiation, B, plus that absorbed from solar radiation reflected back from the earth's atmosphere, C, plus the infra-red radiation absorbed from the earth, D. Thus for a spherical capsule in a circular orbit:

$$Q = W + B + C + D$$

and

$$W = Q - B - C - D$$

where

$$Q = \pi d_o^2 \varepsilon_{IR} \sigma T_s^4$$

$$B = (1-a_v) S \mu_T \frac{\pi d_o^2}{4}$$

$$C = (1-a_v) S \frac{a_E}{\pi} \cos\beta \frac{\pi d_o^2}{4}$$

$$D = 188.5 \, \varepsilon_{IR} \frac{\pi d_o^2}{4}$$

S = Solar constant, 1400 watts/meter^2

T_s = Skin temperature, °K

d_o = Outer diameter, meters

σ = Stefan-Boltzmann constant = 5.67×10^{-8} watt/meter^2 - °K^4

ε_{IR} = Infra-red emissivity of outer skin

a_v = Visual albedo of skin

μ_T = Eclipse factor (see Appendix III) which varies between 1/2 to 1

a_E = Visual albedo of earth (≈ 0.34)

β = Angle that orbital plane makes with earth-sun line

The allowable internally generated heat load is maximum when Q is at a maximum and B, C, and D are at a minimum. In practice, this means that to allow the maximum internal heat load the following conditions must be met:

1. Infra-red emissivity of the surface, ε_{IR}, should be as high as possible.
2. The skin temperature, T_s, should be as high as possible.
3. The capsule surface area should be large.
4. The absorption coefficient, $1-a_v$, of visible radiation should be as low as possible.

5. The orbit should be chosen so that the satellite spends the maximum time in the earth's shadow.

Of the above items, 3 and 5 may be considered fixed by the operational requirements. The maximum skin temperature that we will consider is 70°F (desired cabin temperature). The design value is likely to be about 30°to 40°F less to permit heat transfer from cabin air (forced circulation) to the outer skin. (See Figure 3-1.) A skin temperature of 45°F (280°K) may be assumed.

The permissible internal heat load for a capsule in a given orbit, therefore, depends on attaining surface emissivities having high values for infra-red emissivities and low absorptivity for solar radiations. One such surface that might be considered is a coating of lead carbonate white paint (ref. 27) which has $\varepsilon_{IR} = 0.95$ and $a_v = 0.95$. Considering a 2-meter diameter capsule at 100 miles altitude, the maximum tolerable internal heat load W is approximately 3.5 kilowatts, as seen from Figure 3-1. (A deviation of ± 20°F from the temperature assumed above would result in a ±20% change in W.) For this limiting case, the maximum tolerable internal heat load is relatively unaffected by altitude or orbital inclination. If an uncoated titanium surface ($\varepsilon_{IR} = 0.8$, $a_v = 0.2$) were used for the capsule skin, internal power generation would be impossible without an additional refrigeration system. For the example chosen, a 100-mile circular orbit spending maximum time in the shade of the earth, the average equilibrium skin temperature of the titanium surface for one complete orbit would be approximately 99°F (310°K). To permit high heat dissipation, surface characteristics must be controlled.

Wall construction affects application of these results to passive temperature control of the capsule. Capsule wall structures more complicated than the single shell seem favored to withstand re-entry heating. One solution advanced to minimize temperature rise in the capsule due to aerodynamic heating during re-entry is the use of a double shell structure. This would reduce the value of W (heat generated in the capsule) in orbit considerably unless the cabin air could be circulated between the two shells. Any other obstacle placed between the outer wall and the cabin air would serve as additional thermal resistance and reduce the value of W, the reduction depending on the nature of the obstacle.

The single shell mentioned above, however, offers possibilities of dehumidification by condensation on the cold wall. Although this point is considered further in Section 3.4, it is pertinent to point out at this time that air at 70°F and 50% relative humidity has a dewpoint of 52°F. This means that any surface in contact with air that has a temperature lower than this will gradually condense water out. The single metal shell offers negligible resistance to heat flow. Therefore, inner and outer surface temperatures may be considered about the same. Thus the 30°to 40°F skin temperature considered in this discussion is lower than needed. Possibilities exist for temperatures even lower than these as the average temperature fluctuates with respect to time and position in the capsule. These variations are considered in greater detail in Appendix III.

ALLOWABLE INTERNAL HEAT LOAD AS A FUNCTION OF OUTER SKIN TEMPERATURE AND OVERALL COEFFICIENT OF HEAT TRANSFER FROM INTERIOR TO SHELL

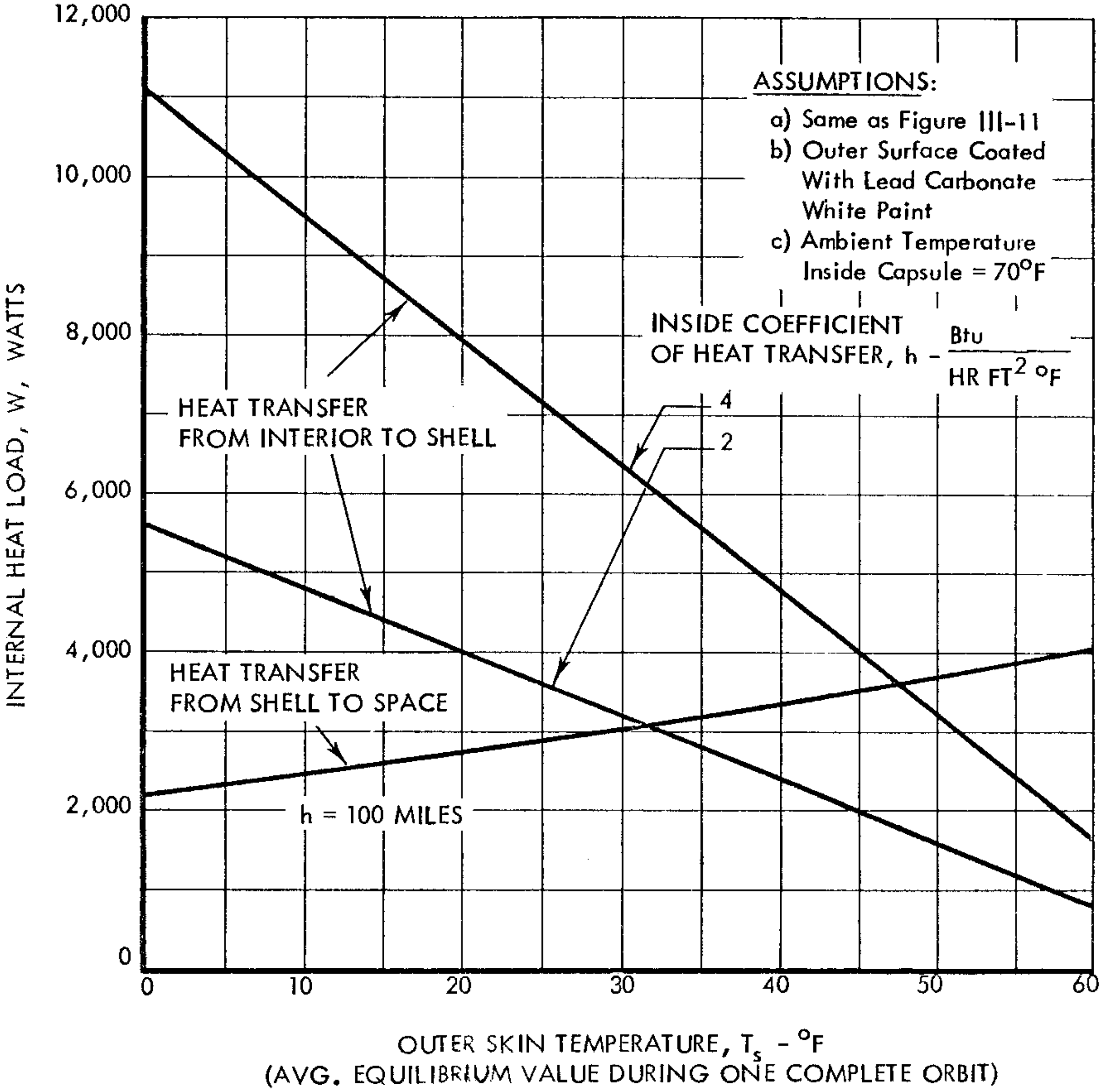


FIGURE 3-1

The above discussion on internal heat load dissipation by a monotonic temperature gradient from cabin air to space shows that a considerable heat load probably can be dissipated. If the heat loads that can be handled in this manner are exceeded, one may resort to supplementary solutions. For example, additional radiating surface in the form of a space radiator may be attached to the capsule. Another general approach is to isolate the hotter components in one part of the cabin volume and insulate them from the occupant compartment. Higher skin temperatures in the vicinity of this hot compartment will not only increase the heat dissipation per square foot of surface in this area, but at the same time will cut down the loading for the occupant compartment. If necessary, additional cooling of the occupant compartment may be accomplished by mechanical refrigeration with heat being rejected at a much higher temperature through coils brazed to the inside of the outer shell or a separate space radiator.

In summary, temperature control of the capsule atmosphere offers no particular problems for relatively low internally generated heat loads. These can be handled by a proper selection of surface characteristics. The surface characteristics need not be homogeneous over the entire surface area. A wide range of overall surface characteristics may be achieved by coating various areas of the capsule with two dissimilar coatings. The upper limit for this type of temperature control and the range of application for the other suggested solutions depend on all the parameters related to capsule structure and to operational requirements. This dependency constitutes one of the strongest arguments for a completely integrated system study of all aspects of a capsule designed for a specific mission.

If a refrigeration system should be needed, the weight burden will eventually fall on the power supply. Section 5.0 shows that cryogenic hydrogen and oxygen offers the best prospects as a power supply from the viewpoint of fuel consumption. At the same time, the cryogenic fluids offer a very effective additional cooling capacity that may be used directly.

3.2 OXYGEN SUPPLY

The following methods were considered for supplying necessary oxygen to the occupant:

1. Storage of molecular oxygen as a compressed gas
2. Cryogenic storage of molecular oxygen
3. Deriving oxygen from chemical sources
4. Deriving oxygen from waste products:
   a. Electrolysis of water
   b. Regeneration of O_2 from CO_2 by chemical methods
   c. Regeneration of O_2 from CO_2 by biological methods

3.2.1 Storage of Molecular Oxygen as a Compressed Gas

This is the most obvious, simplest, and probably the most reliable of all the methods considered but suffers from excessive weight of required containers. The minimum storage weight is obtained by use of spherical tanks. Because this shape does not often use most effectively the volume enclosed by the vehicle envelope, cylindrical container weights and other compromises should be evaluated for optimum weight-to-volume ratios. Formulas for weight-to-volume ratios for spherical and cylindrical containers may be readily derived in terms of the geometrical factors of length (l) and radius (r), the storage pressure, (P), and the properties of the container, density and design stress (S).

A comparison of such equations shows that for the same pressure and allowable design stress, a cylindrical vessel is at least 34% heavier than a sphere of the same volume. This ratio of sphere-to-cylinder weight can be expressed as a function of P/S and l/r. Similar correlations have been developed for vessels composed of spherical zone elements. It has been shown, for example, that the weight-to-volume ratio and strain for a spherical zone design is equivalent to the sphere. The pressure vessel design theory for tank geometries likely to be of the greatest interest to the space vehicle designer considering gas storage seems well established. Differences in weight-to-volume ratios for a given geometry stem largely from the selection of container material, design stress, and operating pressure.

Stress analyses do not recognize that a practical minimum exists for shell thickness which is based primarily on practical considerations rather than stress analyses. This minimum results from fabrication limitations, mounting requirements, resistance to denting and deceleration. In a thorough study, a criteria for this minimum should be established for materials that might be used for the shell structure, and stress-computed thicknesses should be checked against the practical minimum before computation of shell weights.

Preliminary weight analyses indicate that minimum weight considerations slightly favor low pressure storage of oxygen, because oxygen at low pressures and ambient temperatures has a lower compressibility factor. (The compressibility factor is based on generalized plots of PVT data for the common gases.) The system weight (spherical tank plus gas weight)/ pound oxygen, as computed in Appendix IV, is 1.66 to 1.80 pound system/pound O_2.

The pressures considered were 70 to 7000 psia. As indicated, minimum weight considerations favor storage at lower pressures; however, the additional weight penalties (over and above the tank weight) imposed on high volume containers dictate a compromise. This would probably result in a system-to-gas weight ratio somewhere between 1.66 and 1.80 pounds system/pound 0_2.

System weight ratios versus mission duration for pressurized oxygen are shown as part of Figure 3-2. Obviously, the dependence of the ratio on shorter mission durations, especially for lower pressures, is due to the minimum structural thickness of 1/16 inch imposed on the design.

SYSTEM WEIGHT VS MISSION DURATION
FOR MOLECULAR O_2

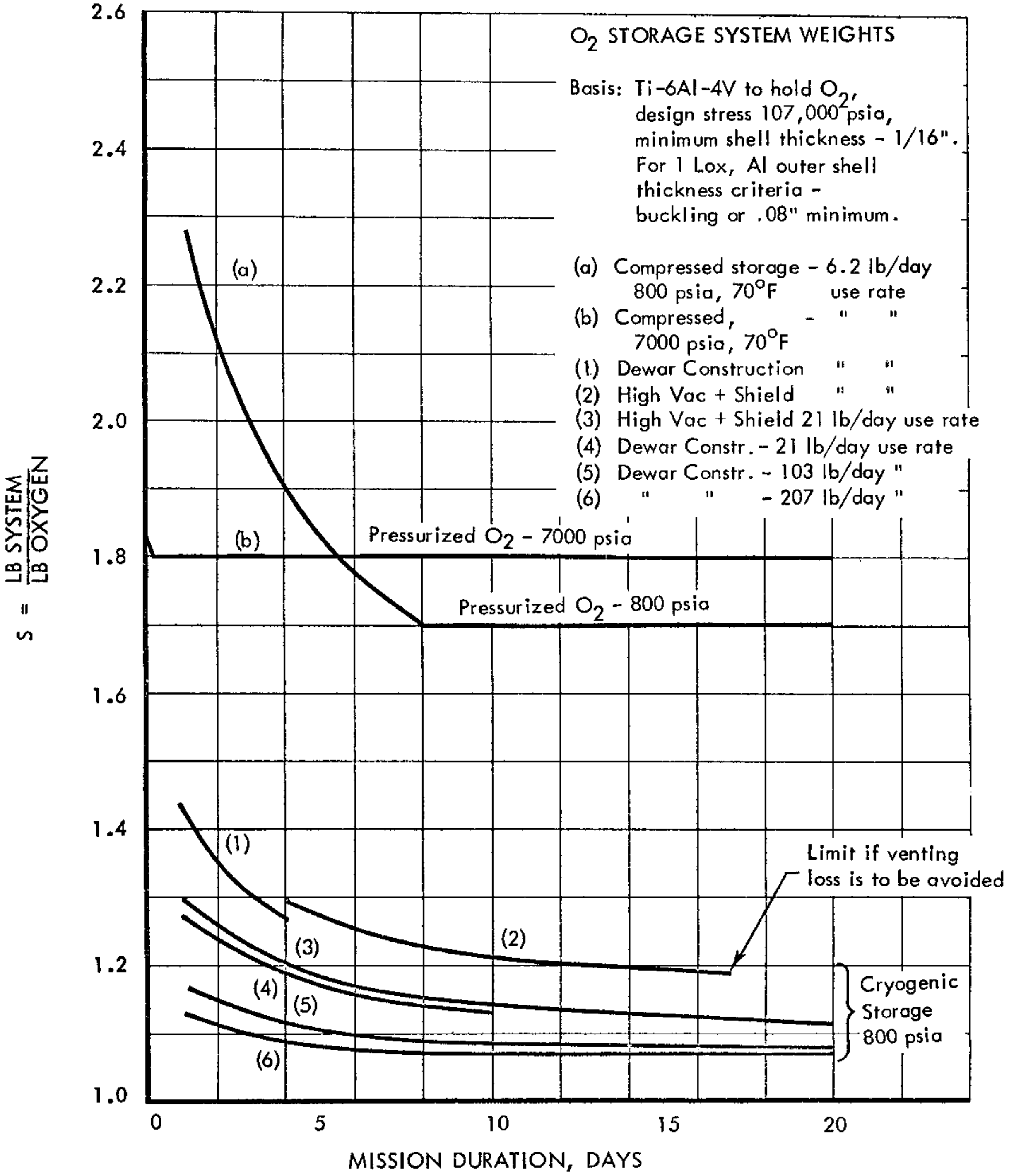


FIGURE 3-2

3.2.2 Cryogenic Storage of Molecular Oxygen

Cryogenic storage offers an obvious weight and volume advantage for the storage of all except the most modest quantities of gases. A weight and volume analysis of this storage method (with reliability comparable to pressurized gas storage) would be the first step in establishing the area where cryogenic storage is preferable to pressurized gas storage. However, the ultimate selection cannot be established without considering integration of the storage system in the overall vehicle concept. The cooling available from cryogenics, for example, cannot be assessed from a weight or volume viewpoint without considering the environmental system requirements as a whole.

In any system storing a cryogenic liquid, the inevitable transfer of heat into the liquid will ultimately evaporate the liquid or build up pressure in the container. If the liquid is not insulated sufficiently, venting over and above the use rate will be necessary, resulting in needless loss of material. If the liquid is over-insulated, that is, if the insulation does not allow enough heat input to produce the required evaporation rate, the penalty is the additional weight not only of excessive insulation, but also of the evaporator that may be required. A logical design consideration in cryogenic storage is the insulation needed for the anticipated use rate.

The use rate is one of the two major parameters considered to evaluate the insulation requirements; the other is the duration of time in which the fluid is to be used. The longer the duration, the greater the need for more effective insulation for any given usage rate. While the degree of insulation required for a given use rate and mission duration will, to a large extent, determine the system weight and volume necessary for a cryogenic gas supply, it is evident that other practical factors must also be considered before the designer is fully equipped to select a cryogenic weight and volume. Minimum shell weights compatible with the material of construction, dynamic forces developed during acceleration and deceleration, fabrication limitations, and possible pressurization required for other uses within the vehicle should be established.

It is obvious that with the ranges in use rate and mission durations possible, all degrees of insulation from simply insulated shell structures to Dewar type construction containing gas-cooled shields or some of the specially developed powders or insulation laminates such as Linde SI-4 will find application in space vehicle design.

The principles of cryogenic container design are well established and are amenable to both analytical and graphical representation. The main uncertainties in weights relate to the material used for construction of the inner shell, the minimum wall thickness of the outer shell when Dewar construction is used, and, as usual, weights and mountings of the accessories required in the proposed applications.

Because cryogenic storage is important in power generation from chemical fuels, a subsystem study of cryogenic oxygen storage weight ratios was made (see Appendix IX). The results are summarized in Figure 3-2 as a function of various use rates and mission duration The abrupt endings on curves (2) and (4) show the duration limit for the indicated insulation if venting losses are to be prevented. The system weight is based on the use of a Ti-6 Al-4V inner shell, an aluminum outer shell, and due to other applications within the capsule requiring high pressure, an operating pressure of 800 pounds/ square inch.

Since a pressurized gas storage system results in a system weight ratio of approximately 1.65 to 1.8 pounds/pound O_2, cryogenic storage offers weight savings for all missions between one and twenty days for the indicated use rates. It should be noted that the system weight ratios for cryogenic storage are dependent on the amount stored and the length of storage time. These factors do not exert any appreciable influence on pressurized gas storage system weight ratios so long as minimum thickness considerations do not control. Thus, if the use rate over and above that required for human consumption can be augmented by other requirements (for an auxiliary power unit, for example), the system weight charged to the man can be reduced and the cryogenic storage system will compare even more favorably to other oxygen storage systems. The importance of making comparisons from a systems viewpoint is once again emphasized.

The system weight ratios shown in Figure 3-2 are much lower than those currently available in hardware for either compressed or cryogenic storage, primarily due to the use of titanium which has a high strength-to-weight ratio and to the use of a high design stress (107,000 psia). Additional information is necessary to evaluate the possible effects of low temperatures on the design properties of titanium. For cryogenic storage, further savings over present hardware were effected by designing the outer shell on its ability to resist collapsing with an external pressure of 15 psia. The thickness so computed was generally less than the minimum thickness allowed for fabrication (0.08 inch). This may be less than thicknesses found in current hardware, but it is believed that present containers are over-designed for space applications. This is an area requiring further study.

3.2.3 Deriving Oxygen from Chemical Sources

Many available chemical compounds could be used to prepare oxygen. The considerations here will be limited to those supplying the highest theoretical yield per pound of chemical. The list presented in Table 3-1 has been derived from a generalized list of oxidizers and has been restricted to those compounds which are not considered toxic and which yield essentially pure oxygen. Thus the oxides of nitrogen, nitric acid,and the nitrates have been excluded, as the product gases will in all probability contain appreciable quantities of nitrogen oxide which may be considered extremely toxic. Ammonium nitrate and ammonium chlorates, in addition to having this disadvantage, are also potentially explosive.

TABLE 3-1

OXYGEN PRODUCERS

Compound	lb Compound/lb Oxygen
H_2O_2	2.1
LiO_2	1.62
NaO_2	2.29
KO_2, K_2O_4	2.96
MgO_4	1.84
CaO_4	2.08
$LiClO_4$	1.66
$NaClO_4$	1.91
$KClO_4$	2.16
$Mg(ClO_4)_2$	1.74
Compressed Oxygen:	lb System/lb Oxygen
70°F and 70 psia	1.66
70°F and 800 psia	1.70
70°F and 7000 psia	1.80
Cryogenic Oxygen:	
800 psia	1.07

Comparing the theoretical yield with compressed gas or cryogenic oxygen sources, it becomes obvious that, if the only purpose of the compounds is to supply oxygen, compressed gas or cryogenic oxygen is better, particularly if one adds container weights to the above compounds. Other factors that may contribute to an even more unfavorable weight ratio for the compounds is the energy or additional chemical that may be required to release oxygen. Exothermic compounds are likely to be penalized because of the additional load they will impose on the cooling system and/or space radiator. Some of the above compounds may appear more favorable as oxygen sources if additional weight-saving functions may be assigned to them. Thus, H_2O_2 is capable of producing not only oxygen, but water and energy as well; the metallic peroxides and superoxides could supply oxygen while absorbing carbon dioxide and water vapor from the environmental atmosphere. The relative merits of these materials when used in this manner cannot be assessed without a system study. This has been deferred to subsequent sections. At this point it is sufficient to indicate reactions in which oxygen would be produced by the compounds in question. These are indicated in Table 3-2.

TABLE 3-2

POSSIBLE REACTIONS FOR PRODUCING OXYGEN

		Catalyst			Heat Evolved/lb O_2
(1)	H_2O_2	$\longrightarrow$	H_2O	$+ 1/2O_2$	+2650 Btu
(2)	$2LiO_2$	$+ H_2O \longrightarrow$	$2LiOH$	$+ 1\text{-}1/2O_2$	
(3)	$2NaO_2$	$+ H_2O \longrightarrow$	$2NaOH$	$+ 1\text{-}1/2O_2$	+900 Btu
(4)	$2KO_2$	$+ H_2O \longrightarrow$	$2KOH$	$+ 1\text{-}1/2O_2$	+ 10,000 Btu
(5)	MgO_4	$+ H_2O \longrightarrow$	$Mg(OH)_2$	$+ 1\text{-}1/2O_2$	
(6)	CaO_4	$+ H_2O \longrightarrow$	$Ca(OH)_2$	$+ 1\text{-}1/2O_2$	
(7)	$KClO_4$	$+$ heat $\longrightarrow$	KCl	$+ 2O_2$	+18 Btu

3.2.4 Deriving Oxygen from Waste Products

Various writers have noted the possibilities of regenerating oxygen from the electrolysis of water (from moisture removed from cabin air and/or urine), and regenerating oxygen from carbon dioxide by chemical, electrochemical, thermal or biological processes. Biological recycling methods, for example, have been considered ideally suited for supplying the environment for the occupant, for they not only regenerate oxygen and remove carbon dioxide and water vapor, but also provide a potential food source in the carbohydrates, fats and proteins that may be formed. The various possibilities are analyzed in Appendix V. The conclusion is the same in every case; namely, such processes require so much energy per pound of oxygen generated that one cannot hope to save any weight over competitive systems they might replace so long as the required energy is derived from chemical energy stored on board. These regenerative processes are more likely to find application with solar or nuclear energy where the weight penalty is essentially independent of duration.

Consequently a detailed discussion of the prospects of regeneration of oxygen from waste products is beyond the intent of this study of a chemically fueled power system. Although considerable research and development work is centered in regenerating oxygen from carbon dioxide by various schemes described briefly in subsequent sections, the work is still in very early stages. Present estimates of efficiencies, weights and volumes would be largely speculative, making possible comparisons practically worthless.

One might consider for a moment, however, the electrolysis of water which is a relatively simple process with efficiencies of the order of 75% or higher. Disregarding the weight of the electrolytic cell hardware, it would be of interest to make a quick estimate of the weight of a solar or nuclear power source that could be used to supply the necessary energy for the electrolysis. A 100% efficient process requires 1660 watt-hours/pound O_2. At 75% efficiency one would require 2220 watt-hours/pound O_2 or 4440 watt-hours/day or a 184-watt unit. Based on the latest weight for solar cells (5.25 watts/pound for solar unit intended for Ranger) a 35-pound solar cell unit would be required to meet the daily oxygen requirements. Using electrical power from a solar-turbo unit of the Sunflower type (4.4 watt/pound) would require 42 pounds. Using electrical energy from a nuclear-turbo unit of the SNAP II type (5 watts/pound) would require 37 pounds without the biological shielding requirements. (These wattages per pound are based on a 190-watt unit for the solar cells; for the others they are based on a 3-kilowatt unit that might also supply power for other needs in the capsule.)

The values of 35, 37, or 42 pounds, therefore, may be regarded as the minimum weight penalties for supplying the oxygen requirements for one man by the electrolysis of water. A cryogenic storage system supplying oxygen to a chemically fueled power unit of 1-kilowatt rating would have a systems weight ratio that would depend on the duration; for a three-day mission it would be less than 1.2 pound system/pound O_2 or 2.4 pounds per day. Therefore no solar or nuclear power source in the present state of the art having power rating of the order of 3 kilowatts could compete with a cryogenic oxygen supply system for durations less than 14 to 15 days. Consequently it may be concluded that pending the evaluation of chemical oxygen supply sources that may serve dual functions, the most promising oxygen supply system is molecular oxygen, preferably stored as a cryogenic fluid.

3.3 CARBON DIOXIDE REMOVAL

As concluded in Section 2.0, about 2.2 pounds of CO_2 must be removed per day per man and the concentration maintained at less than 4 millimeters mercury with a total pressure of 5 psi. This concentration corresponds to approximately 1.5% in an essentially oxygen atmosphere.

Various possibilities for CO_2 removal have been reviewed. These may be classed generally as non-regenerative and regenerative. In the non-regenerative category possibilities for CO_2 control by chemisorption and by freezing out were reviewed; in the regenerative class processes based on the recovery and recycling of the solid or liquid solvent and on photosynthetic and electrochemical reduction of carbon dioxide were considered.

3.3.1 Chemisorption

Table 3-3 presents a list of selected chemicals that react with carbon dioxide and their theoretical CO_2 absorption capacity.

TABLE 3-3

SELECTED CARBON DIOXIDE CHEMISORBERS

Chemical	Theoretical Capacity lb chem/ lb CO_2
LiOH	1.09
MgO	0.92
Li_2O	0.68
LiO_2	1.77
NaO_2	2.50
KO_2	3.32
$Ca(OH)_2$ + NaOH (Soda lime)	2.0
$Ca(OH)_2 + Ba(OH)_2 \cdot 8H_2O$ (Baralyme)	2.0
NaOH	1.82
KOH	2.54

Practically all of these materials have been studied by the Naval Research Laboratories (NRL) since the early thirties relative to the CO_2 control problem in submarines. (Ref. 45)

LiOH

The use of LiOH for CO_2 removal is well established in non-regenerative CO_2 control systems and from a weight ratio viewpoint is not to be challenged by any other material except Li_2O or MgO. The reaction between lithium hydroxide and carbon dioxide may be written as follows:

$$2LiOH + CO_2 \longrightarrow Li_2CO_3 + H_2O: \quad \Delta H = -1200 \text{ Btu/pound LiOH}$$

Thus theoretically when 1 pound of LiOH reacts with 0.92 pound CO_2, 1200 Btu are given off or 1300 Btu/pound CO_2 absorbed. The hydroxide is made by pressing lithium hydroxide monohydrate into cubes or pellets at high pressure to develop a suitable hardness of the material. The cubes or pellets are then crushed and sized to recover 4-14 mesh material. This material is dehydrated and loaded into canisters on a vibrating packing machine.

There is a dust problem associated with the use of LiOH. Although the dust from LiOH canisters is a small portion of the total weight, the sensitivity of some personnel to traces of the dust makes it imperative that an efficient filter be used. Of the filters that have been tried, impregnated fluted-paper filter used for aircraft jet-engine low-pressure fuel filter (specification AN 6236-3) has given the most satisfactory results according to NRL. As most of the dust is formed in handling or in transit, it has been found sufficient in many cases where pressure drop considerations are important to use the filters only during the first few minutes when using the canister.

The capacity of LiOH for CO_2 under dynamic conditions is primarily a function of the absorption rate. The rate of absorption of CO_2 by LiOH is governed not only by the laws of gaseous diffusion into the granule but also by the relative humidity. The 4-14 mesh has been selected by the Navy as a compromise between the conflicting requirements of small particle size for maximum rates, and large particles for minimum pressure drop and blower power requirements.

The beneficial effects of water vapor on the absorption rates are well established. Figure 3-3 shows that using 2% CO_2 in the gas stream and gas velocities of 33 pound/minute, the CO_2 concentration in the exit air becomes significant at 38 minutes and reaches a concentration 85% that of the inlet air in 1 1/4 hours when using dry air. Only 28% of the potential CO_2 absorption capacity was realized over this interval of time. Using humid air (91% RH), however, breakthrough was delayed for 1 1/2 hours and the effluent gas did not reach 85% of the inlet gas concentration until five hours after the start of the test. By this time 100% of the CO_2 absorption capacity of the LiOH was realized. The reason why the relative humidity is important in the light of the fact that water is formed in the above reaction of LiOH and CO_2 is not clear. For example, when 2% CO_2 is being absorbed from air, enough water is liberated to equal 2% of the gas stream. This corresponds to a partial pressure of 152 millimeters mercury for the water vapor at 760 millimeters mercury total pressure which is equivalent to 60% RH at 77°F. In spite of this, the liberated water is less effective in promoting absorption than that in the gas phase. (Soda lime, incidently, behaves similarly.) Also, it appears that as little as 8 to 10% RH air is as effective as much higher relative humidities.

EFFECT OF HUMIDITY ON CO_2 ABSORPTION RATE AND CAPACITY FOR LIOH

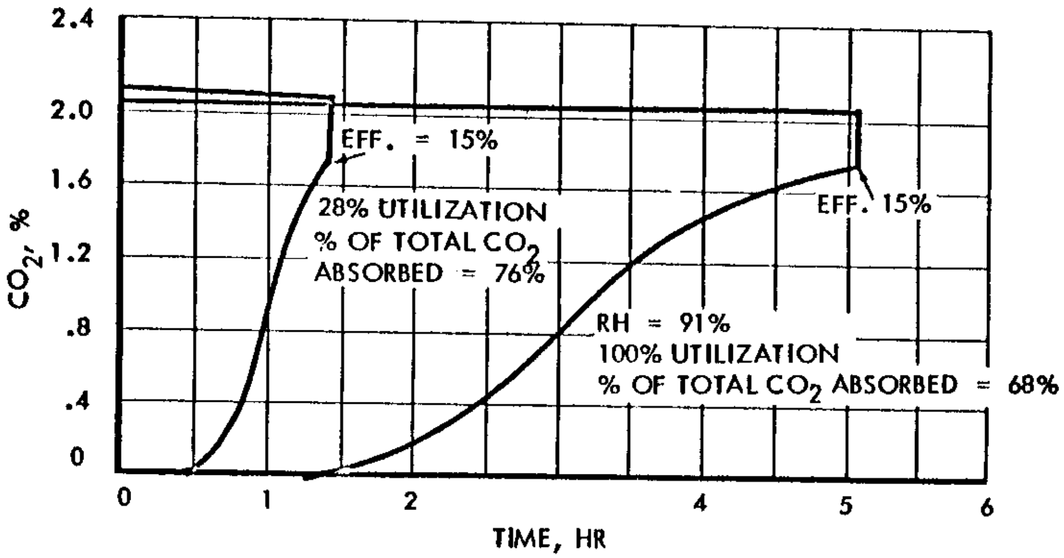


FIGURE 3-3

Concerning the effect of other variables, NRL has shown that temperatures from 70°C to -10°C have no adverse effect on the absorption capacity.

Air Reduction Co. (Ref. 46) has also studied LiOH for CO_2 absorption and has concluded that no differences in absorption capacity have been found that could be ascribed to differences in CO_2 concentration. This result is to be expected since the equilibrium constant of the reaction is so large. This organization also investigated the effect of flow velocity by changing the length-diameter ratio of the LiOH bed, keeping both the absorbent bed volumes and volumetric gas flow rates constant. (This results in higher linear velocities in the narrower bed but the same contact time in both beds.) No essential difference was observed at flow velocities less than 80 feet/minute. The higher flow rates tended to give erratic results due to non-uniform flow or channeling. Baffling and firm packing were recommended to minimize this tendency.

All of the performance data desired is not readily available; however, the information on a LiOH naval unit (Ref. 45) will permit evaluation of a CO_2 absorber of this type. This unit consists of five canisters (each 6-1/2 inches diameter, 12 inches long, holding 6.3 pounds of LiOH), placed in parallel in a manifold. Air is drawn through the five canisters, forced through a filter and into the atmosphere. The unit has a 1/12-horse power AC motor with a centrifugal blower capable of developing 2 to 2-1/2 inches of water head.

At a flow of air through the canisters of 50 to 65 cfm (10 to 13 cfm per canister, assume 12 cfm is the average flow), the pressure drop is 2 inches of water. A total of 5·6.3 = 31.5 pounds LiOH are used which should theoretically pick up 5.8 pounds CO_2 per canister, or 29.0 pounds CO_2 total for saturation. Table 3-4 shows data collected for the five canister unit run in a sealed laboratory room. Carbon dioxide was metered into the room to replace that removed by the absorbent. The relative humidity was between 50 and 60%.

TABLE 3-4

LIOH CANISTER PERFORMANCE

CO_2 conc., %	Cycle, hr	Theoretical Cycle, hr	Saturation, %	CO_2 removed/ canister, lb	CO_2 absorption rate, lb/hr/canister
3.0	7.0	2.35	99	5.7	0.815
1.5	6.5	4.7	93	5.4	0.83
0.75	14.0	9.4	92	5.3	0.38

Figure 3-4 gives typical data for part of a run with 0.8% CO_2 concentration

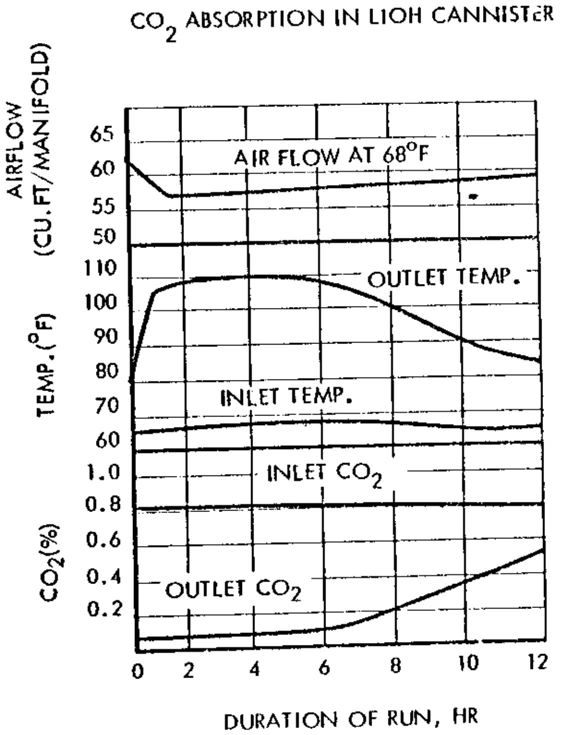


FIGURE 3-4

It will be noted that, as typical of all processes involving fixed bed kinetics, the absorption rate is higher in the beginning of the test than later. For times beyond 6 hours in Figure 3-4, for example, one may conclude that the unreacted bed length is too short to give the required contact time at the flow rates indicated, resulting in increasing CO_2 concentration in the effluent gas stream.

Tests of these canisters aboard an operating submarine gave the following percentage saturations as average values: The carbonate in the spent material in the torpedo room averaged 86.5% over 133 hours of operation, in the control room 92.6% over 136 hours, in the stern room 84.2% through 130 hours. The runs were made while holding CO_2 at the 1% level. These percentages may be regarded as the lower limit of what may be expected under variable operating conditions.

One might also cite Green's data (ref. 19) on a canister 12 x 20 x 50 centimeters, containing 10.37 pounds LiOH (2-8 mesh), "Under one set of circumstances all of the CO_2 and HOH production of two men was absorbed by one canister for 75 hours without refill. The CO_2 was maintained at less than 0.5% and the humidity at approximately 75%. By the end of 75 hours the weight of the LiOH had increased to 21.12 pounds." (This represents a weight increase of 104% and would only be possible if water is absorbed and/or $LiHCO_3$ is formed.) "Double screen baffles placed at distances varying from 10 to 20 centimeters reduced channeling and permitted maximum absorbency by the LiOH."

The bed had a resistance of 3.5 millimeters H_2O for a flow of 250 liters/minute. The use of a glass wool filter 1.5 centimeters thick to remove LiOH dust increased the resistance to 5 to 8 centimeters H_2O for a flow of 230 liters/minute, using the same motor-blower combination.

There is a serious inconsistency in Green's performance data. Certainly both the CO_2 concentration and the relative humidity could not have been maintained over the period mentioned. Assuming even a basal metabolism of 1760 kilocalories/day for a male 25 years old, the CO_2 output is 1.5 pounds/day, while the respiration is 0.55 pound /day and perspiration is 0.78 pound /day (ref. 20). Thus a total of 2.83 pounds of mass for man per day would have to be absorbed. This becomes 17.0 pounds tor two men for three days and may be compared with 10.75 pounds of mass actually absorbed. However, the significant point is that 1 pound of LiOH will absorb a little more than 1 pound of mass which apparently includes both CO_2 and water.

The survey of LiOH for CO_2 absorption may be concluded by stating that the theoretical capacity of LiOH for CO_2 is 1.09 pounds LiOH/pound CO_2. This capacity may be realized in practice if sufficient time is allowed for the CO_2 to be absorbed and if the relative humidity is at least 8 to 10% and preferably higher. To allow for possible channeling in the bed and appreciable absorption rate even at the cutoff point, a value of 90% of the saturation capacity or 1.2 pound LiOH per pound CO_2 absorbed may be considered satisfactory for design purposes. Dryden (ref. 21) gives an actual value of 1.35 pounds LiOH/pound CO_2 absorbed).

MgO

This material was also studied by NRL (Ref. 45), but results showed that the oxide absorbed too slowly for practical use.

Li_2O

No information is available on this material, so it may be said that its use remains to be developed. From a weight-ratio viewpoint, it is the most attractive prospect. Li_2O may be converted to the hydroxide by picking up moisture (0.6 pound/pound Li_2O), so potentially it can meet more of the environmental requirements than LiOH. The main uncertainty lies in the rate at which the material can react. To a large extent, this would depend on the preparation of Li_2O to form a highly porous structure.

LiO_2, NaO_2, KO_2

These superoxides may be handled collectively since they behave similarly as far as is known. Lithium superoxide is known to exist, but at the present time only KO_2 and NaO_2 are being made. The latter is being prepared in small amounts. Although the use of NaO_2 would probably result in significant weight savings over KO_2, it remains to be tested.

These materials have been of great interest in environmental control because they offer the prospect of practically complete control of the environment: in picking up moisture and CO_2 from the air, they release oxygen. In addition, they exert a powerful oxidizing influence and would probably remove traces of hydrogen, hydrocarbons and other organic contaminants which are capable of being oxidized. Acidic gas traces would undoubtedly be removed as well.

The reactions that take place may be approximated as follows:

a. $2KO_2 + HOH \longrightarrow 2KOH + 1.5O_2$

b. $2KOH + CO_2 \longrightarrow K_2CO_3 + HOH$

c. $K_2CO_3 + 1.5HOH \longrightarrow K_2CO_3\ 1.5H_2O$

$$\sum_a^c = 2KO_2 + 1.5HOH + CO_2 \longrightarrow K_2CO_3 \cdot 1.5H_2O + 1.5O_2$$

In the overall reaction as written, the theoretical molar ratios of KO_2:HOH:O_2:CO_2 are 2:1.5:1.5:1, while actual tests have shown the relative ratios to be 2:1.1:1.5:0.9. The water, oxygen and carbon dioxide ratios metabolized by a man not perspiring noticeably will be 3:1.3:1.0. The inequality between the superoxide and human performance ratios, especially the variability of the latter, would indicate an excess of oxygen or a deficiency in the moisture and CO_2 handling capabilities so that it would be fortuitous if a perfect balance were maintained indefinitely. Nevertheless a complete study has been made by NRL (ref. 22) using KO_2 in canisters for air purification with satisfactory results and tests were scheduled on the USS Sailfish with a full crew to maintain the atmosphere at 3% CO_2 and not less than 17% O_2 for 24 hours. Using 14 to 16 pounds of KO_2 per canister, the CO_2 absorption rate and O_2 evaluation were sufficient to accommodate 30 to 40 men per canister. The percentage of KO_2 used up in tests lasting between 1.2 to 1.5 hours varied from 81 to 100% and averaged 93%. Very recently WADD also successfully sustained a man in a closed environment for seven days using KO_2 in sheet form.

Soda Lime, Baralyme, etc.

There is little incentive for considering these materials because of the large weight penalty in comparison to LiOH. Dryden (ref. 21) indicates that 2.9 pounds of soda lime or Baralyme are actually required to absorb one pound of CO_2.

3.3.2 CO_2 Removal by Freezing Out

Theoretically, any heat sink available in the cabin that has temperatures lower than those corresponding to the desired partial pressure of CO_2 in the environment could be used to remove CO_2 from the air. Thus if it is desired to maintain a CO_2 partial pressure of 4 millimeters mercury in the gas phase, heat sinks below −126.5°C must be available. Thus CO_2 could be frozen directly on vehicle surfaces that are colder than this or by heat exchange with cryogenic fluids carried on board.

For direct freezing on the interior skin surface, much depends on the orbit chosen, vehicle orientation, geometry, and wall design. External and internal heat balances establishing surface temperatures for various points on the surface as a function of time would indicate the prospects for the removal of CO_2 by this method. Sublimation of CO_2 could pose a real threat to the occupant unless the CO_2 were thrown overboard before re-entry, or unless the CO_2 were thermally insulated or removed from possible heat conducted to it during the re-entry stage. Our preliminary thermal balances indicate only relatively small heat sink capabilities are required to make this prospect attractive.

Effort devoted to consideration of the engineering problems involved should be commensurate with the difficulties and weight penalties associated with alternate materials for solving the CO_2 problem. For our purposes the possibility of heat exchange with cryogenic fluids is more realistic and is amenable to a preliminary analysis within the scope of this work.

The preliminary analysis of removal of CO_2 by heat exchange with cryogenic fluids, discussed in Section 6.0, showed that possibilities for CO_2 removal by this method depend on the heat content of the fluids, their use rate (i.e., pounds/hour), and the approach temperature assumed for heat exchange sizing. In the case of H_2-O_2, the cryogenic fluids considered in this study, if the use rate of these gases for the power unit is not greater than about 1.2 pound/hour, the heat sink available will not be sufficient to remove the CO_2 generated per man in a direct exchange of energy from the air stream to the cryogenic gases.

The minimum use rate can be lowered to about 0.6 pound H_2-O_2/hour if the air entering the exchanger is precooled with the cool air (free from CO_2 and HOH) exiting from the hydrogen heat exchanger which operates at the lowest temperature level. A combined use rate of about 1.05 pounds of gases/hour will supply both the chemical fuels for a one-kilowatt fuel cell and the man's oxygen requirements. With this use rate for a three-day mission, however, exchanger weights exceed the weights of a LiOH absorption system so use rates would have to exceed the minimum use rate by a factor of at least 4 to 6 before this method could be considered seriously. This would require cryogenic use rates equivalent to 2.5 to 3.5 kilowatts. With power levels much less than this, the heat exchanger weights would be excessive and CO_2 might re-enter the atmosphere during periods of low power demand unless dumped overboard periodically. Dumping would require additional equipment, so even at a 2.5 to 3.5 kilowatt power level, freezing out of CO_2 would be impractical unless the LiOH system weight becomes excessive (i.e., for missions longer than 6 to 10 days). Thus further engineering studies of CO_2 removal by freezing with cryogenic fluid are required for power levels and mission durations beyond these.

3.3.3 Regenerative Sorption Systems for CO_2 Removal

This category includes chemical systems which absorb or adsorb CO_2 and which may be regenerated by heating, cooling and recirculation. Naval personnel have been investigating both solid and liquid systems for removing CO_2 from submarines for many years.

Solid Adsorbents for CO_2 Removal

Solid adsorbents capable of regeneration include silver oxide, activated carbon, aluminum and silica gels, and molecular sieves.

The main difficulty with silver oxide is that the reaction rate is poor. The system was studied at Northwestern University (Ref. 47) and although data necessary to determine the size of equipment are limited, the required system weight and volume appear impractical. Three reactors, each 0.6 cubic foot, would be required to handle the output for one man. The unit would require 0.16 kilowatt of power and would operate on a two-hour cycle. Other disadvantages are that silver oxide is toxic when present in the air in small amounts and that decomposition of the silver carbonate formed will not stop with the regeneration of silver oxide but will tend to decompose to silver, especially at the higher regeneration temperatures.

Activated carbon, alumina and silica gels are of such low capacity (see Figure 3-5) by weight at ambient temperatures that the weight and bulk of regenerative units are prohibitive for a reasonable cycle time in the proposed application.

Molecular sieves are synthetic zeolites quite similar to many natural clays. Chemically they may be considered as alkali metal-aluminosilicates. They owe their effectiveness as CO_2 adsorbents to a large surface area and carefully controlled pore size. Molecular sieves have a greater affinity for water than CO_2, so in the presence of water vapor the

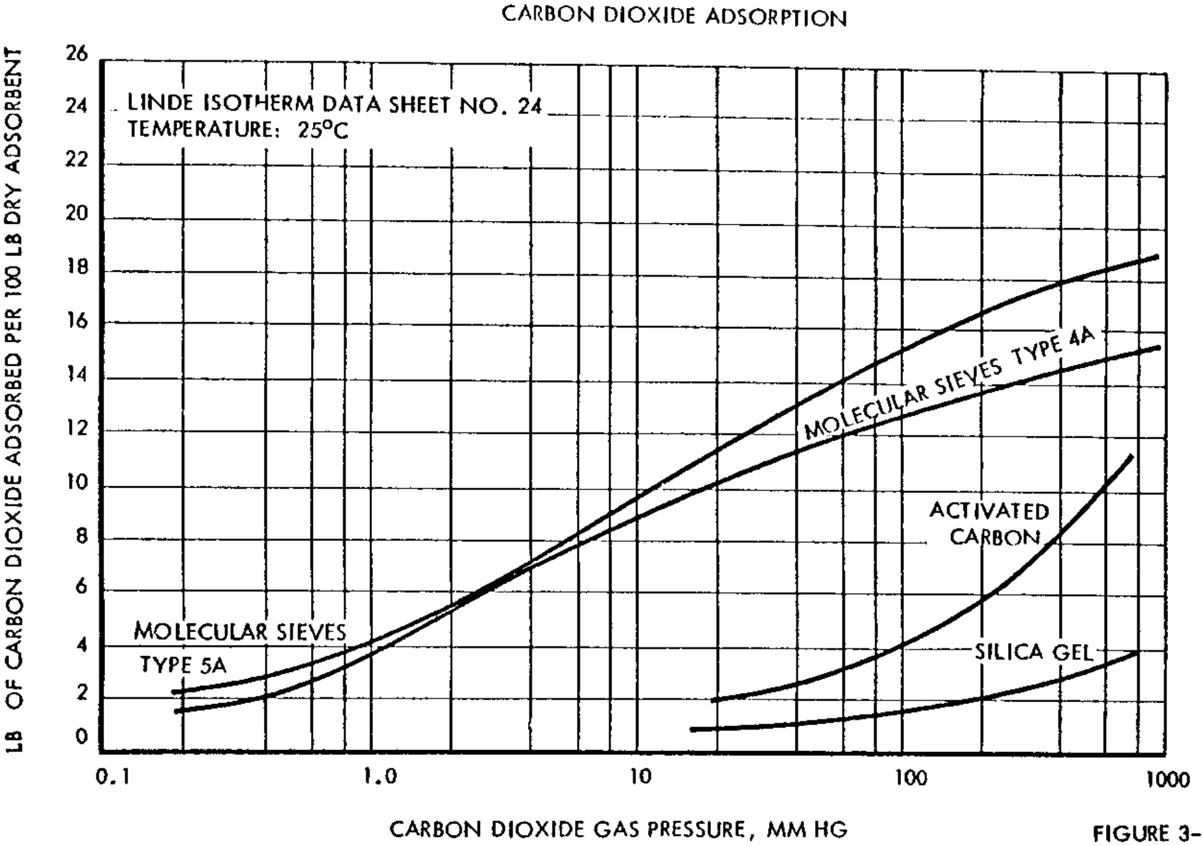


FIGURE 3-5

first component to be adsorbed is water; no other components of the gas will be adsorbed until all the water has been removed. In such an adsorbent bed, the lower part of the bed will be used for water removal and the upper part for the removal of CO_2.

The adsorption capacity of molecular sieves for CO_2 is dependent on the temperature, the concentration of CO_2 in the gas and the amount of water vapor. Adsorption isotherms of molecular sieves, supplied by the Linde Company where the material is undergoing development, are shown in Figure VI-2 of Appendix VI. Considering the characteristics of the material under dynamic conditions, the dynamic capacity is reduced by about 25% over 2000 cycles.

Molecular sieves are regenerated by heating. The rate of regeneration is aided by the use of a purge gas to sweep out the CO_2 evolved or the use of vacuum. The higher the regeneration temperature, the easier it is to regenerate; however, the life is also shortened, especially in the presence of water vapor.

For our application, the use of two adsorption units is recommended, one adsorbing, while the other is being regenerated and subsequently cooled.

For estimating the weight of molecular sieves required for the simultaneous adsorption of CO_2 and water vapor, the Linde Company recommends (Ref. 48) 3-1/2% loading for CO_2 and 10% loading for water vapor. For regeneration under vacuum, they recommend a temperature of 400°F for two hours.

Comparisons of environmental systems using molecular sieves have been made (see Appendix VI). These analyses indicate that the energy required for regeneration makes the process non-competitive with the use of LiOH (or heat exchange for CO_2 removal), and heat exchange for dehumidification if the energy is applied in electrical form from chemical energy sources. The potential value of these systems lies in the use of solar, nuclear or by-product heat. In any case, the hardware weight and charges of molecular sieves required do not justify their use for one-man missions of less than 15 to 16 days.

Liquid Absorption Systems for CO_2 Removal

Because liquid systems are normally handled more easily than solid adsorption systems in recycling processes, they have been examined in considerable detail for CO_2 removal since World War II. Processes using both organic and inorganic compounds in aqueous solutions have been evolved. For example, solutions of alkaline hydroxides as well as aqueous solutions of alkaline amines have been investigated in considerable detail and have been used successfully for CO_2 control in submarine test runs. The Girdler Corporation has investigated a wide choice of chemical agents (Ref. 49), including amines and amine derivatives. Their studies revealed several promising materials that have been used singly or in combination at least on a pilot-plant scale. These include monoethanolamine (MEA), diethanolamine (DEA), methyldiethanolamine (MDA), and diethylene glycol amine (DEGA). The best prospect among these was concluded to be MEA (4.5N) and scrubbing units using this solution are now used in nuclear submarines. A water solution of the potassium salt of the amino acid, N-methylalamine, more commonly known as Alkazid M, now appears to be even better than MEA since it has a lower vapor pressure and better oxidation resistance.

A typical scrubbing system for CO_2 removal by MEA solution is shown in Figure 3-6. Air containing CO_2 is fed to the adsorption tower, with MEA solution flowing countercurrent to the air stream. The CO_2 is then regenerated by heating and stripping in a second column that may be considered a regenerator. The CO_2 exits at the top of the column; the stripped MEA solution exits at the bottom and, after heat exchange, flows back to the top of the absorption unit. Typical performance (ref. 23) from units built for the Navy are as follows:

		Extrapolation for one man
CO_2 removal rate (at 1% inlet)	8 lb/hr	0.1 lb/hr
Power consumption	5 hp	0.0625
Electrical heat consumption	12 kw	0.15
Quantity of air handled	140 CFM	1.75
Total volume	90 ft^3	1.13
Total weight	4100 lb	51.

If this unit is scaled down to handle the CO_2 requirements for one man (0.1 pound/hour), the values in the second column result. While there is some question of the validity of such results based on an 80:1 reduction ratio, the extrapolated values may be regarded as optimistic since it is extremely unlikely that improvements could be affected in going from a large to small unit. (Actually the reverse is generally true.)

From a weight viewpoint, this system would not compete with LiOH at 2.6 to 3 pounds use rate/day for 17 to 20 days.

While the large system was optimized for volume rather than weight, extrapolated value of 51 pounds for the small unit approximates the weight of a small system optimized from a weight viewpoint. The energy required for the small unit should be more readily acceptable as minimum values, since heat losses are proportionately greater for a small unit and power units are likely to be less efficient. The total power requirements are approximately 200 watts. If the 200 watts are derived from an H_2-O_2 power system carried on board (weight penalty 2.5 pounds/kilowatt-hour), the weight penalty is approximately 0.5 pound /hour or 12 pounds/day compared to 2.6 to 3 pounds of LiOH that the scrubbing system would replace. Assuming that heating could be obtained as by-product heat from the power unit, the electrical power requirements (0.0625 horsepower = 46 watts) represents a weight penalty of $0.046 \cdot 2.5 \cdot 24 = 2.76$ pounds/day. This is practically equivalent to the daily LiOH require-

CO_2 SCRUBBING WITH MEA

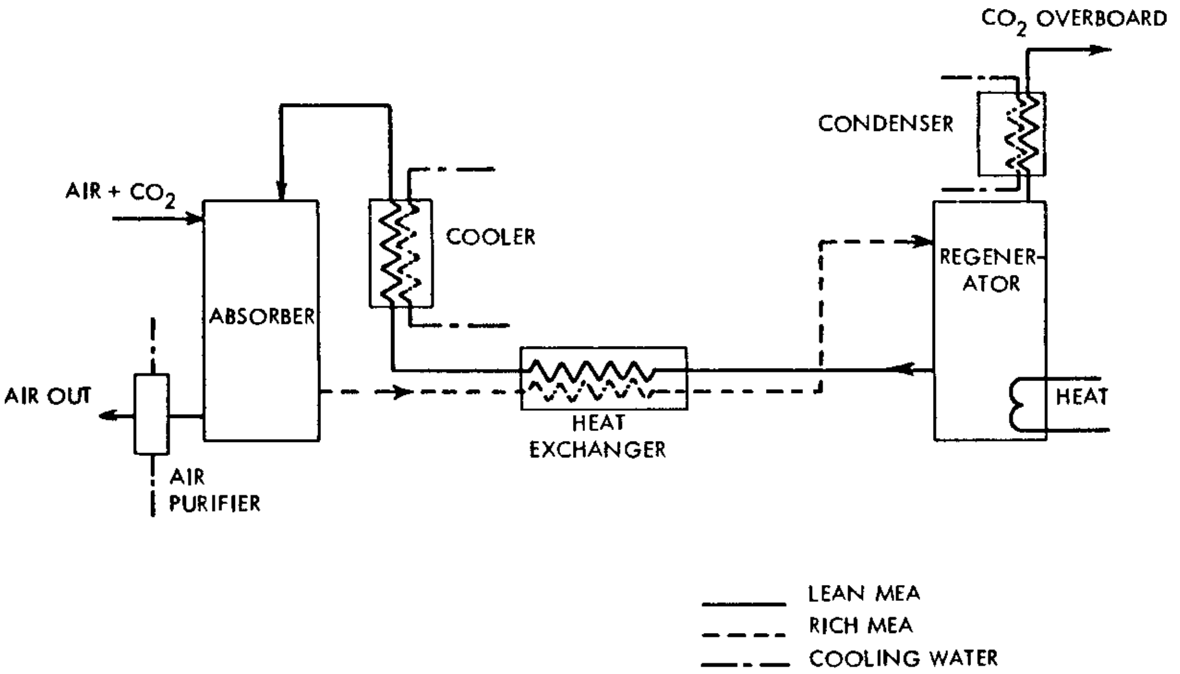


FIGURE 3-6

ments that the system would replace. Obviously, with the present state of the art ethanolamine scrubbing systems have no place in space systems where the energy requirements are derived from stored energy (excluding nuclear) carried on board. While brevity forbids a detailed discussion of other factors that might be considered, the phase separation problems involved with these systems in a gravity-free state and the toxicity and stability of the absorbents involved are additional unfavorable factors.

Alkali carbonate solutions (2N) used for absorbing CO_2, operating at atmospheric pressure and regenerated by heating to 212°F, have also advanced to the prototype stage for submarine application. Typical performance using a jet scrubber is as follows

CO_2 removal rate at 1% inlet	10 lb/hr
Power consumption (for pumping)	5 hp
Heating load if electric	46 hp
Total volume requirements	60-70 ft^3

From the viewpoint of energy required, this system is even worse than the MEA system performance discussed above and may therefore be dropped from further consideration for the proposed application.

An interesting modification of a regenerative-type absorption process for CO_2 removal which results in by-product hydrogen and oxygen is known as the Smith cycle. A flow sheet of the process contemplated for submarine use is shown in Figure 3-7.

In essence the process is as follows: Electrolysis of a Na_2SO_4 solution produces NaOH, H_2SO_4, H_2 and O_2. The NaOH is sent into an absorption tower in which CO_2 from the air is removed, forming Na_2CO_3. This solution is then reacted with the sulfuric acid solution from the anolyte compartment, releasing CO2 which may be rejected overboard and forming Na_2SO_4 again which is sent back to the electrolytic cell. The reactions may be summarized as follows:

In the anolyte compartment of the electrolytic cell:

$$2SO_4^{--} + 2H_2O = 2H_2SO_4 + O_2 + 4e' \qquad (1)$$

In the catholyte compartment of the electrolytic cell:

$$4Na^+ + 4H_2O + 4e' = 4NaOH + 2H_2 \qquad (2)$$

The overall reaction in the cell is (1) + (2), i.e.:

$$4Na^+ + 2\,SO_4^{--} + 6H_2O \longrightarrow 4NaOH + 2H_2SO_4 + 2H_2 + O_2 \qquad (3)$$

SMITH CYCLE

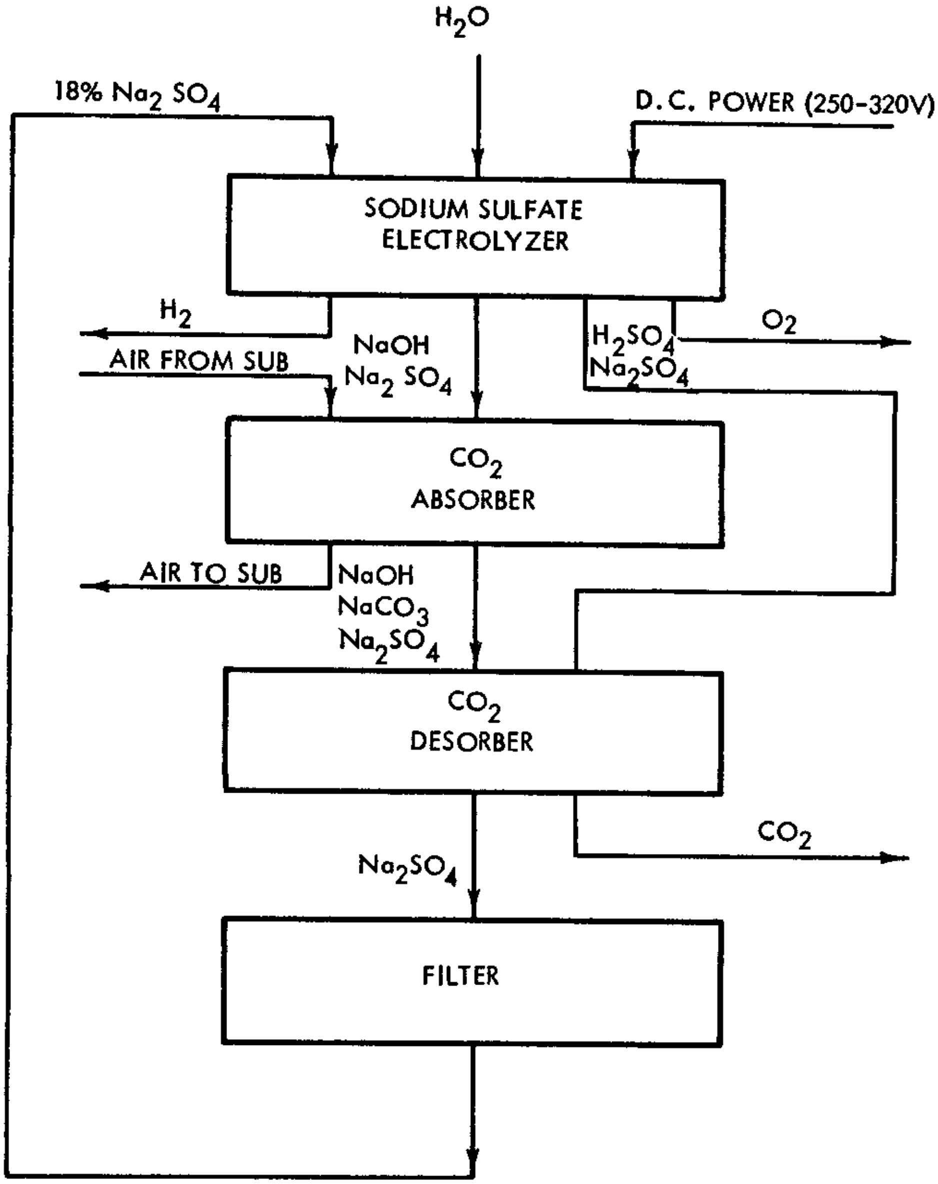


FIGURE 3-7

In the CO_2 absorber:

$$4NaOH + 2CO_2(C_1) \longrightarrow 2Na_2CO_3 + 2H_2O \qquad (4)$$

In the desorber:

$$2Na_2CO_3 + 2H_2SO_4 \longrightarrow 2Na_2SO_4 + 2H_2O + 2CO_2(C_2) \qquad (5)$$

The overall process is the sum of (3) + (4) + (5), or:

$$2H_2O + 2CO_2(C_1) \longrightarrow 2H_2 + O_2 + 2CO_2(C_2) \qquad (6)$$

In such a process the overall reaction is the electrolysis of water and the simultaneous concentration of CO_2 from its partial pressure in the original air (C_1) to essentially pure CO_2 at the system pressure (C_2) according to Equation (6). Only water and DC power are required and CO_2 and H_2 are rejected overboard. Power requirements estimated for a CO_2 removal rate of 10 pounds/hour were 88 horsepower. Since this is 100 times that required for one man, 0.88 horsepower or 650 watts of power would be required for one man. At an average weight penalty of 2.5 pounds power system/kilowatt-hour, the weight penalty for power alone would be 1.6 pounds/hour or 38 pounds/day. The daily oxygen and LiOH requirements for one man can be supplied with a weight penalty of about 2.5 pounds in cryogenic oxygen and about 2.7 to 3 pounds for LiOH or a total of 5.2 to 5.5 pounds. Thus, even assuming that excess water is available from an H_2-O_2 power unit, the weight penalty for a chemical power source alone to supply electric power to the process is about seven times that of the system it would replace.

3.3.4 Photosynthetic and Electrochemical Reduction of CO_2

Various writers have proposed the use of photosynthetic methods of recovering CO_2 and at the same time regenerating oxygen and perhaps foodstuffs. While this may be considered the ideal solution of the environmental control problem, it has been shown in Appendix V that such processes are a practical impossibility as long as the energy required for the regeneration comes from chemical energy carried on board. The same may be said of various electrochemical reduction schemes that have been proposed where the overall reaction may be written as:

$$CO_2 \longrightarrow C + O_2$$

Consideration of CO_2 reduction methods must therefore be limited to the use of solar or nuclear power sources which are considered outside the scope of this study.

3.4 DEHUMIDIFICATION

Condensation, non-regenerative sorption methods and regenerative sorption methods have been considered for the removal of moisture from the cabin air. Compression-cooling-condensation was not considered because it obviously cannot compete, from the standpoint of either equipment or power, for the modest requirements implied in this study.

3.4.1 Condensation

Condensation can occur on the inner walls of the vehicle if the walls are below the dew-point of the environmental atmosphere, i.e., 52°F at 50% relative humidity and 70°F. Whether or not condensation can be used will depend largely on the surface area of the capsule and the internally generated heat load. For a 2-meter diameter spherical shell this method becomes feasible if the internally generated heat loads are less than 3 to 4 kilowatts for a capsule externally coated for maximum visual albedo and maximum infra-red emissivity. This method would probably not involve any weight penalties. Its potential value would be determined to a large extent by the thermal balance around the vehicle, so further consideration must be postponed until a total systems study and temperature analysis of various points of the vehicle selected have been made for the orbit chosen.

Condensation by heat exchange between cabin air and cryogenic fluids can also be used for dehumidification if the use rates are large enough. This method has been examined in considerable detail in Appendix X because of its applicability in the $H_2 - O_2$ cryogenic system chosen to meet the capsule's power and environmental requirements.

The dehumidification requirements can be met with H_2-O_2 use rates greater than about 1 to 1.2 pounds/hour. Requirements can be met using even smaller quantities of H_2-O_2 if an additional heat exchanger is used for heat-sink recovery. Further details are discussed in Section 6.0.

Any unit that may be used to cool the cabin air can accomplish dehumidification as long as the cooling surface temperature is below the dewpoint of the cabin air at the desired humidity and temperature. Thus where cooling of the air is required, dehumidification imposes no weight penalty except that acquired in removing the condensed moisture from the cooling surface. In a gravity-free state and with conventional heat exchanger design this might pose a major problem.

3.4.2 Sorption Methods - Non-regenerative

Relatively few materials ordinarily classed as desiccants for drying of gases are at the same time considered non-regenerative, because most materials do not have a very high capacity, and dehumidification with regeneration is a simple process for a relatively large number of materials, both solids and liquids. Anhydrone (magnesium perchlorate), which has a saturation capacity of about 0.5 pound H_2O/pound dry desiccant and which is difficult to regenerate, may be considered the best example of non-regenerative materials. Other materials in the non-regenerative category, with multi-functional capabilities in an environment control system are lithium hydroxide (LiOH), potassium superoxide (KO_2), and lithium oxide (Li_2O).

Lithium hydroxide, for example, can pick up 0.75 pound H_2O/pound LiOH to form the monohydrate, but its capacity for CO_2 absorption decreases. At the same time the rate of moisture pickup is relatively slow. No specific studies have been made of LiOH for the simultaneous absorption of CO_2 and water vapor. Potassium superoxide has been discussed previously and so need not be detailed here.

Lithium oxide could theoretically combine with 0.6 pound H_2O to form lithium hydroxide according to the following reaction:

$$Li_2O + HOH \longrightarrow 2LiOH$$

The LiOH could absorb additional water to form the monohydrate with a total pickup of 3 mols of water/mol of Li_2O or 1.8 pounds H_2O/pound Li_2O. Presumably most of the absorption capacity for CO_2 would still be retained. Theoretically, if $Li_2CO_3 \cdot H_2O$ were formed from Li_2O, HOH and CO_2 according to the reaction

$$Li_2O + H_2O + CO_2 \longrightarrow Li_2CO_3\ H_2O$$

the water load would control the amount of Li_2O required. For 2.5 pounds HOH/day, 4.2 pounds of Li_2O would be sufficient to pick up the water vapor as well as the CO_2 evolved. This system might merit further study.

Other substances, such as LiCl (2.8 pounds H_2O/pound desiccant at 25°C and 50% relative humidity) and $CaCl_2$(1.8 pounds H_2O/pound desiccant at 25°C and 50% relative humidity), might be considered non-regenerative in view of their high capacity; these materials are seldom used, however, because before the high capacity is realized the substances become deliquescent and for practical purposes may be considered as concentrated solutions. This phase change from the solid to the liquid complicates the handling problems as well as use of these materials in non-regenerative systems.

3.4.3 Sorption Methods - Regenerative

From the engineering viewpoint humidity control regenerative systems may be divided into two categories: solid phase and liquid phase. Both types have found extensive use in dehumidification. Typical of the liquid-phase systems are those employing solutions of LiCl, $CaCl_2$, H_2SO_4, NaOH, KOH, glycerine, triethylene glycol and other glycols. Processes based on these solutions may be operated continuously, with the solutions flowing from one piece of equipment to another during absorption to desorption of the water vapor picked up. They may be handled in the same manner and with the type of equipment that might be used for the removal of CO_2 by the regenerative absorption processes already discussed. Examples of solid phase regenerative dehumidification systems are those employing silica gel, activated alumina, molecular sieves, and drierite. These processes are characterized by intermittent operation; generally the gas is passed through one fixed bed of these porous substances while other beds are being reactivated by heating to drive the water out. Techniques and type of equipment are similar to those for CO_2 removal by molecular sieves.

Silica gel has the highest capacity and the narrowest operating temperature range and would therefore be chosen as the best representative of this group for the intended application. When used for adsorption at 70°F and regenerated at 300°F, about 0.2 pound of water vapor/pound of dry gel may be handled. A 4-pound canister of silica gel may be used for about 8 hours before regeneration. Two canisters may be operated alternately as already described (see CO_2 adsorption with molecular sieves). Some system simplification, especially for short missions, may be effected by manually replacing one canister with another in the air conditioning system while placing the loaded canister in a chamber lock, heated either internally or externally, and opening the chamber to the vacuum of space.

Analytical methods for sizing the equipment and estimating the power requirements are well established for both solid and liquid-phase dehumidification. The main problems anticipated for application to space vehicles are primarily associated with operation in a gravity-free state. Adsorption (solid-phase separation) systems offer no particular problems in this respect if desorption is to take place by exposure to space. If the water is to be recovered, however, one has to contend with the usual problems associated with condensation and collection of the water in a gravity-free state. For absorption systems one has to contend with phase separation problems in both the absorption and desorption steps of the process. These areas would require additional engineering studies if the dehumidification problems could not be handled by condensation.

3.5 WATER SUPPLY

As concluded in Section 2.0, a minimum of 6 pounds of water/day will be required for human consumption. Three possibilities were considered for meeting the requirement: (1) derivation of water from the chemical fuels of the power unit, (2) derivation from ecological wastes, and (3) carrying water on board.

The derivation of water from the chemical fuel system was one of the primary considerations in its selection. This is in harmony with the original objectives of the contract. Fortunately, the H_2-O_2 system which was selected on the basis of power output alone also provides one of the simplest systems available for the production of water. The power unit study showed that any H_2-O_2 use rate above 1/4 pound/hour will meet the water requirements. This level is considered to be around the lower limit of anticipated power requirements, so an adequate supply of water is assured. The selection of the H_2-O_2 system primarily from the point of view of minimum total system weight made it unnecessary to consider other methods in any detail.

The derivation of water from ecological wastes is receiving considerable study at this time by various groups interested in forming a closed system for the man's requirements. Recent announcements of acceptable water distilled from urine indicate that considerable progress is being made in this area. Since fecal water is appreciably less than that formed by food metabolism, it would seem that the derivation of water from fecal matter can be postponed so long as at least dry food is carried on board. This assumes, of course, practically complete recovery of water from urine, perspiration, and respiration.

Water recovery from fluid body wastes seems unjustified so long as water could be derived from an auxiliary power system that derives its energy from chemical systems containing hydrogen and oxygen in any form (i.e., elemental or compound). The survey of chemical energy sources showed that very few chemical energy systems would not result in formation of water as a by-product and these exceptions are not very attractive as power producers. Recovery of water from ecological wastes may be justified when power systems relying on battery, solar, or nuclear power are used or when the power level of a chemically powered APU is too small to meet the daily water requirements. As we have seen, when using H_2-O_2 the minimum water requirements can be met with any unit using 1/4 pound of H_2-O_2/hour. This corresponds to only 1/4 kilowatt for even the most efficient energy converter, namely the hydroxy fuel cell.

3.6 ODOR AND OTHER TRACE GAS CONTROL

Subsystems for odor control present a relatively minor problem from the weight viewpoint, but malfunctioning could lead to serious psychological and physiological consequences for the human occupant. General methods for handling offensive odors include masking, oxidation, and adsorption. Dryden (ref. 21), for example, recommends the use of 0.5 pound of activated carbon/man day. If this were placed in a regenerative type of environmental system pack (i.e., as a section in a silica gel and/or molecular sieve adsorption train), it could be regenerated with the other adsorbents with practically no additional weight penalties. Quite likely, silica gel and especially molecular sieves have sufficient adsorption capacity for these traces, so activated carbon may not even be necessary. Use of KO_2 as an oxidizing agent for odor control in non-regenerative systems was demonstrated as a supplementary advantage in the use of this material for oxygen supply and CO_2 control.

Other trace gases that may be found in the cabin atmosphere and which might prove irritating to the eyes, nose, or throat of the occupant include those resulting from partial degradation of overheated plastic components, wood, etc., and those originating from chemical subsystems (e.g., fuels, oxidants, refrigerant gases). These could include a wide variety of substances (e.g., hydrogen, ammonia, hydrocarbons, carbon monoxide, SO_2, Freons, etc). These are all susceptible to oxidation, adsorption, or chemical reaction removal techniques and should present no major problems. In most cases, methods already proposed for the control of other atmospheric contaminants would remove these. Further details cannot be given without considering the chemical species involved.

3.7 CONCLUSIONS

As we have seen, the problem of temperature control is to keep the capsule cool enough in the face of internally generated heat. Heat from the man and that generated with possible CO_2 removal and dehumidification systems totals less than 700 Btu/hour or 200 watts. This represents about 5% of the heat load that a 6-1/2 foot diameter spherical capsule will handle (about 3.4 kilowatts if the outer surface were suitably treated for maximum heat dissipation by radiation at 44°F skin temperature.) Larger loads may be handled by increasing the size of the capsule, attaching an additional radiator, or raising the skin radiating temperature above 44° F. The latter would require isolation of the occupant compartment and refrigeration to remove the heat generated within the enclosure and by leakage. Additional improvements in the tolerable heat load for a given-sized capsule may be attained by appropriate layout and distribution of the major heat producers in the capsule. Thus the entire problem of temperature control depends largely on the variables related to the capsule design and operational requirement. Until these factors are more clearly specified, the inclusion of a refrigeration system (and certainly its sizing) as part of the environmental equipment pack is an arbitrary matter.

If refrigeration is necessary, the requirements for a system to cool, either by evaporating water into space or by mechanical refrigeration, would depend on the heat load that it must handle. Whatever is decided along these lines will not invalidate the selection of the chemical fuel system or of methods for meeting other environmental requirements, but may be considered as an additional study.

The most promising chemical non-regenerative systems for the remaining major components of the environmental system (i.e., O_2 supply, CO_2 removal and dehumidification) have been evaluated in terms of an integrated system. Table 3-5 is a weight summary of the most promising combinations for meeting the requirements.

System 1 may be considered as the present state of the art. The values of LiCl for dehumidification are based on solid LiCl absorbing HOH until the vapor pressure of water in the solution formed becomes equivalent to 50% RH at 70° F. The problems involved are a matter of materials handling. The application of Li_2O for dehumidification and/or CO_2 removal remains to be developed, and systems using NaO_2 must await availability and parametric studies of the material.

Inspection of Table 3-5 shows that the minimum weight one can hope to achieve with non-regenerative air conditioning systems is 4 to 6 pounds/man day. Beyond this point one has available the prospects of CO_2 removal by freezing with cryogenics and/or re-generation of sorbers for CO_2 and HOH. The latter processes, however, require so much energy for the regeneration that it is unlikely they will find much use in a system that derives energy from chemicals stored on board. The regeneration of oxygen from carbon dioxide or waste water by any practical process that depends on chemical energy sources for power has been ruled out. These regenerative processes must rely on the availability of solar or nuclear power.

TABLE 3-5

SUMMARY OF DAILY WEIGHT REQUIREMENTS OF SELECTED CHEMICAL AIR CONDITIONING SYSTEMS *

System	O_2		HOH		CO_2		Total
1.	Compressed oxygen	3.4 lb	Anhydrone	5 lb	$LiOH$	2.4 lb	10.8 lb/day
2.	Compressed oxygen	3.4	$LiCl$	0.9	Li_2O	1.5	5.8
3.	Cryogenic oxygen	2.4	$LiCl$	0-0.9	Li_2O	1.5	3.9 - 5.8
4.	KO_2	6.0	$LiCl$	0.63	Li_2O	0.37	7.0
5.	KO_2	7.9	Anhydrone	3.0	—		10.9
6.	KO_2	6.0	Anhydrone	3.5	$LiOH$	0.6	10.1
7.	Compressed oxygen	3.4	Li_2O	4.2	—		7.6
8.	Compressed oxygen	3.4	$LiOH$	3.33	$LiOH$	2.4	9.1
9.	Cryogenic oxygen	2.4	$LiCl$	0-0.9	$LiOH$	2.4	4.8 - 5.7
10.	NaO_2	4.6	$LiCl$	0.6	Li_2O	0.37	5.6

* Basis: One man with daily requirements of 2.0 pounds O_2 supply, 2.5 pounds HOH, and 2.2 pounds CO_2 removal (R Q = 0.80).

Other assumptions:

Compressed oxygen is available at 1.7 pounds system/pound O_2.

Cryogenic oxygen is available at 1.2 pounds system/pound O_2.

Li_2O is used either to form $LiOH$ with HOH and/or Li_2CO_3 with CO_2, i.e., hydrated carbonate formation is excluded. So used, one needs theoretically 1.67 pounds Li_2O/ pound HOH and 0.68 pound Li_2O/pound CO_2.

KO_2 requirements are based on actual test results.

NaO_2 requirements are based on same molar conversion percentages as KO_2.

4.0 CHEMICAL ENERGY SURVEY

This study considered all chemical energy sources, regardless of whether or not they could produce by-products useful to man, because use of a single chemical system to supply both power and occupant requirements might increase the weight and decrease the reliability of the system. The criterion of minimum weight and maximum reliability could dictate use of two essentially independent systems.

This section presents compilations of various chemicals that might serve as fuels and oxidizers. The theoretical energy release was computed from thermodynamic data when available; these results aided in a preliminary screening of most combinations. However, although a high-energy chemical system is a necessary prerequisite to a high electrical (and/or mechanical) output per pound of chemicals, it is obvious that the output is dependent on the process and devices used to make the conversion. These problems are deferred to Section 5.0 which considers the most promising prospects found in this preliminary survey from the broader viewpoint of a systems analysis.

4.1 SELECTION CRITERION

The criterion for the selection of the more energetic chemical systems was based on the standard free energy of the reaction. This is the maximum theoretical energy available for the conversion of the chemical energy into mechanical or electrical form for the perfect process of the reactants and products with each at 25°C and 1 atmosphere pressure. (A "perfect process" implies complete combustion, a perfect engine, and no irreversible losses of any kind.) While it is possible to extract more or less energy from a pound of system than indicated by the standard free energy (ΔF) by deviating from the temperature and pressure restrictions imposed on reactants and/or products, such devices are, in theory at least, available to all chemical systems and therefore will not generally affect the relative rank of the systems.

In this survey the enthalpy (ΔH) for the various reactions has also been calculated and tabulated for use in evaluating thermal engine performance. It is common practice to speak of engine efficiency in terms of the thermal energy input into the cycle. In addition, quite often ΔF cannot be computed because data is lacking for a particular component of the reaction. The value of ΔH may be considered in such cases as our tabulations show that for high energy systems the values of ΔF and ΔH are generally within 10% of each other. This is so primarily because ΔH is much larger than $T\Delta S$ for these systems, so ΔF, which equals $\Delta H - T\Delta S$, becomes equivalent to ΔH.

4.2 POSSIBLE FUELS AND OXIDIZERS

Table 4-1 presents a list of high energy fuel sources, many of which will be recognized as important components of well-known fuel systems. The list has been divided into two groups, elements and compounds. The elemental fuels considered are those in Group I to Group IV of the periodic chart.

TABLE 4-1
HIGH ENERGY FUELS AND THEIR THERMODYNAMIC PROPERTIES AT 25°C
Kilocalories/gram mole

Elements*	Molecular Weight	ΔF	ΔH
H_2 (g)	2	0	0
Li (c)	6.94	0	0
Be (c)	9.0	0	0
B (c)	10.82	0	0
C (graphite) (c)	12	0	0
Na (c)	23	0	0
Compounds*			
LiH (c)	7.94	-16.7	-21.6
$LiBH_4$ (c)	21.76	-28.3	-44.6
$LiAlH_4$	37.94	-----	-24.2
BeH (g)	10	-----	-----
BeB_2H_8	38.64	-----	-----
B_2H_6 (g)	27.7	19.8	7.5
B_5H_9 (g)	63.2	39.6	15.0
$B_{10}H_{14}$ (c)	122.3	-----	8
CH_4 (g)	16	-12.1	-17.89
C_8H_{18} (l)	114.1	4.1	-49.8
C_2H_4O (g)	44	- 6.94	-16.1
CH_3OH (l)	32	-39.7	-57.0
C_2H_5OH (l)	46	-41.8	-66.36
$Al(BH_4)_3$	71.46	-33.6	-72.1
HCN (l)	27	29	25.2
$(CN)_2$ (g)	56	70.8	73.6

Elements*	Molecular Weight	ΔF	ΔH
Mg (c)	24.3	0	0
Al (c)	27	0	0
Si (c)	28	0	0
K (c)	39.1	0	0
Ca (c)	40.1	0	0
Ti (c)	47.9	0	0
Compounds*			
NH_3 (g)	17	- 3.98	-11.0
N_2H_4 (l)	32	35.6	12.
$N_2H_2(CH_3)_2$(UDMH)(l)	-----	-----	12.7
CH_3NH_2	-----	-----	-----
$C_6H_5NH_2$ (aniline)	-----	-----	-----
CH_3NO_2 (nitromethane)	61	2.3	-21.3
$C_4H_3OCH_2OH$ (Furfurol Alcohol)	-----	-----	-----
$C_3H_5(NO_3)_2$ (Nitroglycerine)	-----	-----	-----
$C_3H_7NO_3$ (N-Propyl Nitrate)	-----	-----	-(47;49; 57.4)
H_2O_2 (l)	34	-28.2	-44.8
C_2H_2 (g)	26	50	54.2
C_3H_4 (g)	40	46.3	44.3

* (g) Gas, (l) Liquid, (c) Crystalline

Table 4-2 is a compilation of the most powerful oxidants known today. Unfortunately complete thermodynamic data for these materials is often lacking, but other considerations involved in the selection of suitable oxidants for the propellant-atmosphere system eliminate most of the uncommon oxidants anyway. The elemental oxidizers considered are those in Group VII (F_2, Cl_2, Br_2) and Group VI (O_2, S, Se). The various elements considered are summarized in the following periodic order:

I	II	III	IV	V	VI	VII
H						
Li	Be	B	C	(N)	O	F
Na	Mg	Al	Si	(P)	S	Cl
K	Ca		Ti		Se	Br

The elements were assumed to combine according to the following general equations:

Group Combination	General Equation
I - VII	$\mathrm{I} + \mathrm{VII} = \mathrm{I}\cdot\mathrm{VII}$
II - VII	$\mathrm{II} + 2\cdot\mathrm{VII} = \mathrm{II}\cdot\mathrm{VII}_2$
III - VII	$\mathrm{III} + 3\cdot\mathrm{VII} = \mathrm{III}\cdot\mathrm{VII}_3$
IV - VII	$\mathrm{IV} + 4\cdot\mathrm{VII} = \mathrm{IV}\cdot\mathrm{VII}_4$
I - VI	$2\mathrm{I} + \mathrm{VI} = \mathrm{I}_2\cdot\mathrm{VI}$
II - VI	$\mathrm{II} + \mathrm{VI} = \mathrm{II}\cdot\mathrm{VI}$
III -VI	$2\mathrm{III} + 3\mathrm{VI} = \mathrm{III}_2\cdot\mathrm{VI}_3$
IV - VI	$\mathrm{IV} + 2\mathrm{VI} = \mathrm{IV}\cdot\mathrm{VI}_2$

Table 4-3 presents the thermodynamic functions for the products that may be involved.

The values shown were generally computed from data derived from various sources (Ref. 24, 50, 51).

The thermodynamic functions computed (ΔF and ΔH) for the indicated reactions are summarized in Tables 4-6 and 4-7 where values are expressed in kilowatt-hours per pound of combined fuel and oxidant. All values are based on each component in the reaction being in its normal state, at 25°C (77°F) and 1 atmosphere pressure. To conserve space, elements resulting in relatively low values have been omitted from the tabulations. This applies to sulfur, for example, which proved to be much poorer than oxygen. Selenium would show still lower values. The trend for decreasing values with increasing atomic weights is also indicated by a comparison of the values of fluorine versus chlorine as oxidants. Bromine would yield even lower values and iodine would be the worst of all

TABLE 4-2
OXIDIZERS AND THEIR THERMODYNAMIC PROPERTIES AT 25°C

Kilocalories/gram mole

Group A*	Molecular Weight	Compound/ Lb O_2	- ΔF	- ΔH	Group B*	Molecular Weight	- ΔF	- ΔH
O_2 (g)	32	1.0	0	0	O_3 (g)	48	-39	-34
H_2O_2 (l)	34	2.12	28.2	44.8	NO (g)	30	-21.7	-21.6
LiO_2 (c)	38.9	1.62			NO_2 (g)	46	-12.4	- 8.1
NaO_2 (c)	55	2.29		61.9	N_2O_3 (g)	76		
KO_2 (c)	71.1	2.96		134.	N_2O_4 (g)	92	-23.5	- 2.3
MgO_4 (c)	88.3	1.84			N_2O_5 (g)	108		- 3.6
CaO_4 (l)	104.1	2.08			HNO_3 (l)	63	19.1	41.4
NH_4ClO_4 (c)	117.5	1.84		69.4	NO_2F (g)	65		
$LiClO_4$ (c)	106.4	1.66		91.8	NO_3F (g)	81		
$NaClO_4$ (c)	122.45	1.91		92.2	NOF (g)	49		
$KClO_4$ (c)	138.55	2.16	72.7	103.6	F_2 (g)	38	0	0
$Mg(ClO_4)_2$ (c)	223.2	1.74		140.6	Cl_2 (g)	70.9	0	0
NH_4NO_3 (c)	80	5.0		87.3	ClF (g)	54.46	13.6	13.3
$LiNO_3$ (c)	68.95	1.73		115.3	ClF_3 (g)	92.45		4.27
$NaNO_3$ (c)	85	2.13	87.5	101.5	NF_3 (g)	71		27.2
KNO_3 (c)	101.1	2.52	94	117.8	Cl_2O_7 (g)	182.9		-63.4
$Mg(NO_3)_2$ (c)	148	1.85	140.6	188.7	ClO_3F (g)	102.46	22.3	5.1
					F_2O (g)	54	- 9.7	- 5.5

* (g) Gas, (l) Liquid, (c) Crystalline

TABLE 4-3
REACTION PRODUCTS AND THEIR THERMODYNAMIC PROPERTIES AT 25°C
Kilocalories/gram mole

Product*	Molecular Weight	ΔF	ΔH	Product*	Molecular Weight	ΔF	ΔH
H_2O (l)	18	- 56.7	- 68.3	NaCl (c)	58.45	- 91.8	- 98.2
H_2O (g)	18	- 54.6	- 57.8	MgO (c)	40.3	-136.1	-143.8
HF (g)	20	- 64.7	- 64.2	$Mg(OH)_2$ (c)	58.34	-199.3	-221.0
HCl (g)	36.46	- 22.8	- 22.1	MgF_2 (c)	62.32	-250.8	-263.5
Li_2O (c)	29.9	-130	-142.4	$MgCl_2$ (c)	95.23	-141.6	-153.4
LiOH (c)	23.95	-106.1	-116.5	$MgCO_3$ (c)	84.33	-246	-266
Li_2CO_3 (c)	73.9	-270.7	-290.5	Al_2O_3 (c)	101.94	-376.8	-399.1
LiF (c)	25.94	-139.5	-146.3	$Al(OH)_3$ (c)	77.99		-304.2
LiCl (c)	42.4	- 99.2	- 97.7	AlF_3 (c)	83.97	-294	-311
BeO (c)	25	-139.0	-146.0	$AlCl_3$ (c)	133.34	-152.2	-166.2
$Be(OH)_2$ (c)	43		-216	SiO_2 (c)	60.06	-192.4	-205.4
$BeCO_3$ (c)	69			SiF_4 (g)	104.06	-360	-370
BeF_2 (c)	47	-210		$SiCl_4$ (g)	169.9	-136.2	-145.7
$BeCl_2$ (c)	79.9	-141	-122.3	K_2O (c)	94.2		- 86.4
B_2O_3 (c)	69.64	-283.0	-302.0	KOH (c)	56.1		-101.8
BF_3 (g)	67.8	-261.3	-265.4	K_2CO_3 (c)	138.2		-273.9
BCl_3 (g)	117.2	- 90.9	- 94.5	KF (c)	58.1	-127.4	-134.5
CO (g)	28	- 32.8	- 26.4	KCl (c)	74.55	- 97.6	-104.2
CO_2 (g)	44	- 94.3	- 94.0	CaO (c)	56.1	-144.4	-151.9
CF_4 (g)	88	-151.8	-162.5	$Ca(OH)_2$ (c)	74.1	-214.3	-235.8
CCl_4 (l)	153.8	- 16.4	- 33.3	$CaCO_3$ (c)	100.1	-269.8	-288.5
Na_2O (c)	62	- 90.0	- 99.4	CaF_2 (c)	78.1	-277.7	-290.3
NaOH (c)	40	90.6	-102	$CaCl_2$ (c)	111	-179.3	-190.0
$NaCO_3$ (c)	106	-250.4	-270.3	TiO_2 (c)	79.9	-203.8	-218.0
NaF (c)	42	-129.3	-136	TiF_4 (c)	123.9		-370
NH_4Cl (c)	53.5	- 48.7	- 75.3	$TiCl_4$ (l)	189.7	-161.2	-179.3

* (g) Gas, (l) Liquid, (c) Crystalline

from the energy viewpoint. The strongest oxidants are in the upper right hand corner of the periodic table, with fluorine and oxygen being the most powerful of the elemental oxidants.

Concerning elemental fuels, the tabulations show that the most energetic of the alkali metals is lithium, followed by sodium, potassium, etc. Of the alkaline earths (Group II) the best performer is generally the lightest metal, beryllium, followed in decreasing order by magnesium, calcium, and zinc. In Group III considerations may be limited to boron and aluminum. Higher atomic weight elements in the group have lower energy values. In Group IV consideration may be limited to carbon, silicon, and titanium. The peak values are generally manifest in silicon. The most potent elemental fuels are found in the upper left-hand corner of the periodic chart. Thus one may conclude that the most potent combinations of the elements may be formed from a combination of those in the upper left-hand corner with those of the upper right-hand corner of the periodic table.

4.2.1 Screening of Fuels

The number of compounds that exist that may be classed as fuels or oxidizers runs into thousands. The number of possible combinations of these in a chemical reaction is the product of the number of fuels and number of oxidants. Obviously some generalizations to permit weeding out most of the possibilities is mandatory. The energy values obtained for the oxidation of the elements already presented can serve as important aids in the selection of chemical compounds for fuels or oxidizers. To facilitate the selection it has been found convenient to consider the fuels and oxidizers separately.

The calculated energies of the reactions represent the difference between the sum of the energies of the products and the sum of the energies of the reactants, taking into account the appropriate number of moles involved. Thus fuels and oxidants having zero or positive values for their energy of formation and which at the same time result in products having large formation energies (i.e., large negative values on a pound basis) are the most desirable from an energy viewpoint. It is impossible to generalize beyond this point. In many cases, however, the energy of formation of the reactants approaches zero, in which case the energy available depends on the oxidation products. We have already seen that when this is the case, fuels containing Li, Be, B, Mg, Al, C, Si, and H are preferred since their oxidation will release the highest energy. A partial list of such possibilities has already been presented in Table 4-1. Many of these are important components of well-known high-energy propellant systems. Any fuel having a negative value for either ΔF or ΔH is not as potent an energy source as a mechanical mixture containing the same percentage of the individual elements. Obviously from a minimum weight viewpoint it would be absurd to use anything except 100% of the most potent fuel under such conditions. As we shall see later a weight penalty may be acceptable, however, to gain important practical advantages in many cases.

The borane-type fuels, HCN, $(CN)_2$, N_2H_4, and aniline are fuels that possess an inherently greater energy release than the uncombined elements of which they are composed, and thus should be considered further.

A large number of compounds containing only carbon and hydrogen (hydrocarbons) also have positive values. Perry (ref. 24) lists about 70 hydrocarbons in which ΔF is positive. These may be evaluated collectively by the following analysis. Let the oxidation of these hydrocarbons be represented by the general equation

$$C_xH_y + (x + y/4)O_2 \xrightarrow{25^oC} X\,CO_2 + 0.5\,y\,H_2O\,(1)$$

$$\Delta F/\text{pound} = \frac{\Delta F_{CO_2} + 0.5y\Delta F_{H_2O(1)} - \Delta F_{C_xH_y}}{44\,x + 9\,y}$$

The ratio of hydrogen to carbon in the fuel $= y/x = R$.

The value of R varies from a minimum of 1 for acetylene to a maximum of 4 for methane. All paraffinic hydrocarbons, olefins, and all possible unsaturates have values of R between 1 and 4. The above expression for ΔF/pound of fuel and oxidant may be written as

$$\Delta F/\text{pound} = \frac{\Delta F_{CO_2} + 0.5R\Delta F_{H_2O}}{44 + 9R} - \frac{\Delta F_{C_xH_y}}{x(44 + 9R)} = \varnothing_1 + \varnothing_2$$

Since the free energies of formation of both CO_2 and H_2O are negative, it follows from the preceding expression that the free energy of formation of C_xH_y must be positive to yield higher ΔF/pound values than equivalent mixtures of carbon and hydrogen.

We may set a 10% increase in ΔF/pound as significant and worthwhile over a mixture of hydrogen and carbon, and determine the minimum value that $\Delta F_{C_xH_y}$ must have for different values of x and R in order to qualify. Thus, from a numerical viewpoint $\varnothing_2$ must be at least $0.1\,\varnothing_1$ or

$$\begin{aligned}\Delta F_{C_xH_y} &\geq 0.1x\,(\Delta F_{CO_2} + 0.5R\,\Delta F_{H_2O})\\ &\geq 0.1x\,(94.3 + 0.5(56.7)R)\\ &\geq 0.1x\,(94.3 + 28.53R)\end{aligned}$$

Thus for $C_xH_y = CH_4$ the free energy of formation must be at least 21 kilocalories/gram mole.

By comparing the values of ΔF for various values of x and R with the values tabulated by Perry (ref. 24) it may readily be shown that only acetylene, C_2H_2(g), and methylacetylene, C_3H_4(g), have formation energies that exceed the above limits. These are included in the summarized results in Tables 4-6 and 4-7.

Perry also lists the heat and free energy of formation for 35 compounds of carbon, hydrogen, and oxygen. Only four of these have positive free energy values, however, and these values are too small to be significant.

Another large group of compounds listed by Perry which have positive ΔF's (and in most cases positive ΔH) are the amines. None of these are even as good as mixtures of only carbon and hydrogen, for the additional weight of the nitrogen more than offsets the additional free energy it makes available. Of the remaining seven organic compounds listed, only HCN and $(CN)_2$ yield sufficient energy to be classed as high-energy fuels and these are included in Tables 4-6 and 4-7.

4.2.2 Screening of Oxidizers

The oxidants considered (Table 4-2) have been derived from various sources and include the most powerful oxidants known. To permit certain generalizations concerning their use, they have been divided into two groups, non-toxic and toxic oxidants.

Non-Toxic Oxidants (Group A)

In most cases these materials may be readily decomposed to yield relatively pure oxygen if needed. In the case of molecular oxygen stored either as compressed gas or as a cryogenic fluid, the weight ratios presented include the container weight. These weights are subject to many factors so the subject of container weight for oxygen has been handled separately. In view of the fact that cryogenic oxygen offers the best weight ratio of any member of this group, even without considering some container weight for the other oxygen sources, it might be well to review the conditions on which the weight ratio was based. (See Appendix VIII.)

The favorable position occupied by cryogenic oxygen relative to the other substances listed in Group A is further enhanced by the fact that, although the existence of many of the compounds that most closely approach its weight ratio has been established, no information is available on their properties. This includes LiO_2, MgO_4, and CaO_4. Of these, LiO_2 offers the prospect of yielding the largest amount of oxygen of all the superoxides when this substance becomes available.

From an energy viewpoint, however, it is evident that the weight factor is by itself insufficient for determining the relative merits of the materials listed in Group A. For purposes of comparison each compound may be regarded as undergoing decomposition to form oxygen which then combines with the fuel to complete the reaction. Thus any energy released in the decomposition should be considered on the credit side of the compound if this energy is used in a thermal engine to produce power. This would counteract at least some of the unfavorable weight ratio. If, on the other hand, no attempt is made to utilize this decomposition energy, it will probably result in an additional weight penalty for the capsule since it will impose an additional load on any space radiator required.

In either case the energy evolved should be considered for each compound. Based on the following decomposition reaction at 25°C with all materials in their normal states, the results may be summarized as follows:

	ΔF kcal/g mole	ΔH kcal/g mole
$H_2O_2 \rightarrow H_2O + 1/2O_2$	-28.5	-23.5
$2LiO_2 \rightarrow Li_2O + 1\text{-}1/2O_2$		
$2NAO_2 \rightarrow Na_2O + 1\text{-}1/2O_2$		+24.4
$2KO_2 \rightarrow K_2O + 1\text{-}1/2O_2$		+182
$MgO_4 \rightarrow MgO + 1\text{-}1/2O_2$		
$CaO_4 \rightarrow CaO + 1\text{-}1/2O_2$		
$NH_4ClO_4 \rightarrow NH_4Cl + 2O_2$		- 5.9
$LiClO_4 \rightarrow LiCl + 2O_2$		
$NaClO_4 \rightarrow NaCl + 2O_2$		-6.0
$KClO_4 \rightarrow KCl + 2O_2$	-24.9	+0.6
$Mg(ClO_4)_2 \rightarrow MgCl_2 + 4O_2$		-12.8
$NH_4NO_3 \rightarrow 2H_2O + N_2 + 1/2O_2$		-49.3
$2LiNO_3 \rightarrow Li_2O + N_2 + 2\text{-}1/2O_2$		+88.2
$2NaNO_3 \rightarrow Na_2O + N_2 + 2\text{-}1/2O_2$	+103.6	+85
$2KNO_3 \rightarrow K_2O + N_2 + 2\text{-}1/2O_2$		+149.2
$Mg(NO_3)_2 \rightarrow MgO + N_2 + 2\text{-}1/2O_2$	+4.5	+44.9

Thus when the utilization of the above oxidants produces the oxide or chloride in the power production process, only H_2O_2, NH_4ClO_4, $NaClO_4$, $KClO_4$, $Mg(ClO_4)_2$, and NH_4NO_3, of those compounds for which at least one of the energy values may be calculated, show negative energies. The computationsof ΔF and ΔH using H_2O_2 and $KClO_4$, which have the largest numerical values,have been made for all fuel prospects. The value of ΔH has also been computed for various fuels with $Mg(ClO_4)_2$. Of the remaining possibilities (NH_4ClO_4, $NaClO_4$, and NH_4NO_3), a few computations with several fuels indicated that the energy of decomposition did not affect the energy-to-weight ratio significantly. The weight ratio for NH_4NO_3 is so poor relative to the other compounds that it was dropped from further consideration in spite of the favorable energy of decomposition.

Toxic Oxidants (Group B)

Although the possibility exists for deriving oxygen from many of these substances (e.g., O_3, nitrogen oxides, fluorine, and oxy-fluorides), the processes involved for producing atmospheric oxygen would be rather complex and would require additional equipment and energy. Preliminary studies indicated that if these oxidants were to be used for the power cycle, it would be much more economical from a weight viewpoint to carry along a separate atmospheric oxygen source rather than try to obtain it from any of the materials considered in Group B. Our sole interest in these materials, therefore, depends on whether they yield much higher energy-to-weight ratios with the various fuels than the best oxidants of Group A (i.e., cryogenic oxygen, hydrogen peroxide, etc). If so, two practically independent chemical systems, one for power and the other for the occupant requirements may result in the lighter and possibly most reliable system. Proceeding with a preliminary screening of the oxidants listed in Group B we may consider first of all the oxides of nitrogen. The properties of these materials are summarized in Table 4-4.

TABLE 4-4

PROPERTIES OF THE OXIDES OF NITROGEN

	ΔF	ΔH	Lb/Lb O_2	Melting Point	Boiling Point
NO	21.7	21.6	1.87	-164°C	-152°C
N_2O_3			1.63	-102	+ 3.5
NO_2	12.4	8.1	1.44		
N_2O_4	23.5	2.3	1.44	- 11	+ 21
N_2O_5		3.6	1.35	+ 30	+ 47
HNO_3	-19.1	-41.4	1.57	- 42	+ 86
NO_2F				-139	- 63
NO_3F					
NOF				-134	- 56

Since the thermodynamic properties of N_2O_3, NO_2F, NO3F, and NOF are completely lacking, they may be excluded from further consideration. NO is less desirable than N2O4 from an energy as well as storage viewpoint. N_2O_4 would be favored over NO_2 from an energy viewpoint and probably storage as well. Nitric acid is obviously not as desirable as N_2O_4 or N_2O_5 from the energy-to-weight ratio criterion but is considered further because of ease of handling. Thus, of this group, only N_2O_4, N_2O_5, and HNO_3 need be considered further.

Ozone is highly favored from an energy viewpoint and so has been included in further calculations of ΔF and ΔH for various fuels. However, it is not available in concentrated form because of its unreliable behavior (explosive), and in addition is very toxic.

The remaining members of Group B, i.e., the halogenated materials, are generally considered both corrosive and toxic. Their physical properties are summarized in Table 4-5.

TABLE 4-5.

PROPERTIES OF GROUP B MATERIALS

	ΔF	ΔH	Melting Point	Boiling Point	Liquid Density
F_2	0	0	-223°C	-188°C	1.69 g/cc
$C\;_2$	0	0	-103	- 34	3.21
ClF	-13.6	-13.3	-154	-101	1.62
ClF_3		- 4.27	- 83	+ 11	1.77
NF_3		-27.2	-217	-120	1.54
Cl_2O_7		63.4	- 91	+ 82	
ClO_3F	-22.3	- 5.1	-146	- 47	1.43
F_2O	9.7	5.5	-224	-145	1.90

We have already seen from our discussion of elemental fuels and oxidizers that fluorine has a much higher energy-to-weight ratio than chlorine, an advantage which cannot possibly be overcome by the savings in container weight since the container weight is a relatively minor part of the oxidant system weight in either case*. This argument may be extended to include the oxidation of the compound fuels with F_2 or Cl_2. Therefore Cl_2 may be excluded from further consideration.

The compounds ClF and NF_3 will in all probability require the same type of container as fluorine for long durations. Since the liquid densities are comparable the storage tank weights per pound of fluid stored will be comparable. The negative heats of formation will tend to decrease the energy per weight available from these two compounds in combustion with any of the above fuels. Probably an even more important disadvantage in the use of ClF or NF_3 is the fact that Cl or N contribute little or nothing to the oxidation energy. Practically all of the energy evolved is due to fluorine, so that the energy-to-weight ratio using either of these two chemicals would obviously be less than using pure fluorine. For these reasons ClF and NF_3 will not be considered further. One may conclude that from the list of halogenated materials only F_2, ClF_3, Cl_2O_7, ClO_3F, and F_2O remain to be considered in additional detail.

4.3 SUMMARY

The systems surviving the screening process are summarized in Tables 4-6 and 4-7 which show the standard free energies and enthalpies respectively of various fuel-oxidant combinations. Listing the individual reactions upon which each value was based would result in needless detail. However, various assumptions and guides used in the computation should be known before the values are used. These may be summarized as follows:

1. Using O_2 or O_3 as oxidizers, all of the elemental fuels are oxidized to their normal valence oxides.
2. Whenever nitrogen appeared in either fuel or oxidizer, it appeared in the product as N_2.
3. Wherever water was found, the product was assumed to be in the liquid state.
4. Whenever the chlorates or perchlorates were used, the materials were assumed to give up their oxygen to the fuel, and the metal and chlorine appeared as the normal metal chloride in the products.

---

* F_2 container considered analogous to O_2 container, but larger density for F_2 1.7 vs 1.4 for O_2 decreases system weight for F_2 to $1 + (1.4/1.7)(0.08 \text{ to } 0.30) = 1.0666$ to 1.25 pound system/pound F_2. For Cl_2 using same container, $1 + (1.4/32)(0.08 \text{ to } 0.30) = 1.035$ to 1.13 pound system/pound Cl_2.

TABLE 4-6
SUMMARY OF -ΔF FOR HIGH-ENERGY CHEMICAL SYSTEMS
Kilowatt Hours/Pound

	O_3	O_2	N_2O_4	H_2O_2	HNO_3	$KClO_4$	ClO_3F	F_2	F_2O
H_2	2.04	1.66	1.33	1.25	1.17	0.91	1.12	1.71	1.78
Li	2.53	2.3	1.94	2.04	1.81	1.48	2.02	2.84	2.70
Be	3.21	2.94	2.39	2.06	2.17	1.46	2.18	2.36	2.64
B	2.44	2.14	1.68	1.58	1.60	1.27	1.52	2.04	2.14
C	1.44	1.12	0.97	1.00	0.86	0.69	0.67	0.91	1.06
Na	0.88	0.766	0.74	1.01	0.70	0.63	0.86	1.63	1.30
Mg	1.95	1.79	1.59	1.49	1.49	1.28	1.54	2.13	2.09
Al	2.15	1.94	1.65	1.56	1.58	1.32	1.52	1.85	1.94
Si	1.92	1.69	1.46	1.88	1.35	1.11	1.30	1.83	1.84
K								1.16	
Ca	1.48	1.36	1.26	1.33	1.20	1.06	1.28	1.88	1.70
Ti	1.52	1.34	1.21	1.36	1.13	0.97			
LiH	2.26	1.97	1.63	1.49	1.48	1.19		2.15	2.36
$LiBH_4$	2.20	1.87	1.51	1.40	1.37	1.08		1.92	2.12
$Al(BH_4)_3$	2.16	1.81	1.58	1.40	1.33	1.08		1.82	
$LiAlH_4$									

TABLE 4-6 - (Continued)
SUMMARY OF -ΔF FOR HIGH-ENERGY CHEMICAL SYSTEMS
Kilowatt Hours/Pound

	O_3	O_2	N_2O_4	H_2O_2	HNO_3	$KClO_4$	F_2	F_2O	Cl_2
B_2H_6	2.35	2.02	1.62	1.47	1.46	1.54	1.92	2.11	0.39
B_5H_9	2.40	2.08	1.67	1.51	1.51	1.58	1.96	2.05	0.40
$B_{10}H_{14}$									
CH_4	1.63	1.29	1.07	1.08	0.95	0.75	1.25		0.17
C_8H_{18}	1.64	1.30	1.08	1.09	0.97	0.77	1.18		0.15
C_2H_4O	1.55	1.30	1.09	1.09	0.97	0.80	1.08		0.11
CH_3OH	1.38	1.11	0.97	1.00	0.88	0.73	1.06		0.10
C_2H_5OH	1.47	1.18	1.01	1.03	0.91	0.74	0.94		0.07
HCN	1.45	1.19	1.08	1.05	0.94	0.65	1.06		0.18
$(CN)_2$	1.37	1.18	1.01	1.05	0.92	0.78	0.97		0.16
NH_3	1.30	1.04	0.92	1.02	0.83	0.69	1.36		0.28
N_2H_4	1.44	1.23	1.08	1.09	1.01	0.84	1.43		
CH_3NO_2	1.25	1.13	1.05	1.06	1.00	0.89	1.00		0.15
H_2O_2	--	--	--	0.438	--	--	--		--
C_2H_2	1.79	1.47	1.22	1.18	1.09	0.87	1.18		
C_3H_4		1.39		1.15			1.17		

TABLE 4-7
SUMMARY OF -ΔH FOR HIGH-ENERGY CHEMICAL SYSTEM

Kilowatt Hours/Pound

	O_3	O_2	N_2O_4	N_2O_5	H_2O_2	HNO_3	$Mg(ClO_4)_2$	$KClO_4$	ClO_3F	F_2	F_2O	ClF_3	Cl_2O_7
H_2	2.33	2.00	1.45	1.55	1.35	1.27	1.24	0.99	1.37	1.70	1.84	0.94	1.56
Li	2.72	2.53	2.05	2.13	2.08	1.89	1.82	1.55	2.22	2.98	2.84	2.17	2.26
Be	3.32	3.08	2.40	2.54	2.08	2.21	1.70	1.47					
B	2.55	2.29	1.76	1.86	1.59	1.59	1.54	1.27	1.68	2.07	2.18	1.26	1.82
C	1.40	1.13	0.87		0.93	0.75	0.76	0.61	0.77	0.98	1.07	0.44	0.93
Na	0.94	0.845	0.77		1.05	0.72	0.72	0.65	0.97	1.71	1.36	1.33	0.92
Mg	2.03	1.88	1.61		1.51	1.50	1.47	1.29	1.68	2.23	2.12	1.61	1.71
Al	2.24	2.06	1.71	1.78	1.59	1.59	1.55	1.34	1.67	1.96	2.03	1.33	1.79
Si	2.01	1.80	1.47		1.33	1.34	1.31	1.12	1.44	1.88	1.89	1.19	1.53
K	0.55	0.48	0.45		0.75	0.43	0.44	0.41	0.63	1.22	0.91	0.99	0.57
Ca	1.55	1.43	1.28		1.36	1.21	1.19	1.07	1.39	1.96	1.76	1.49	1.38
Ti	1.59	1.44	1.23		1.21	1.14	1.13	0.98	1.22	1.58	1.55	1.05	1.29
LiH	2.34	2.08	1.63		1.49	1.47	1.42	1.18		2.17	2.44		
$LiBH_4$	2.28	2.00	1.53		1.40	1.35	1.31	1.07		1.90	2.24		
$Al(BH_4)_3$	2.26	1.98	1.52		1.39	1.35	1.31	1.08		1.80			
$LiAlH_4$	2.28	2.04	1.61		1.48	1.46	1.41	1.12		1.92	2.03		

TABLE 4-7 - (Continued)
SUMMARY OF $-\Delta H$ FOR HIGH-ENERGY CHEMICAL SYSTEM
Kilowatt Hours/Pound

	O_3	O_2	N_2O_4	H_2O_2	HNO_3	$Mg(ClO_4)_2$	$KClO_4$	F_2	F_2O
B_2H_6	2.49	2.20	1.65	1.49	1.47	1.42	1.16	1.91	2.11
B_5H_9	2.51	2.23	1.69	1.52	1.51	1.45	1.19	1.95	2.12
$B_{10}H_{14}$	2.50	2.22	1.69	1.52	1.51	1.45	1.19	1.96	
CH_4	1.70	1.40	1.05	1.30	1.07	0.91	0.73	1.26	
C_8H_{18}	1.64	1.35	1.02	1.04	0.88	0.88	0.71	1.19	
C_2H_4O	1.57	1.33	1.05	1.06	0.93	0.92	0.76	1.14	
CH_3OH	1.37	1.15	0.87	0.96	0.81	0.81	0.68	1.04	
C_2H_5OH	1.47	1.21	0.95	0.99	0.83	0.83	0.68	0.93	
HCN	1.83	1.21	0.63	1.00	0.86	0.86	0.71	1.09	
$(CN)_2$	1.35	1.19	0.40	1.00	0.84	0.84	0.71	1.03	
NH_3	1.40	1.18	0.95	0.98	0.84	0.84	0.70	1.30	
N_2H_4	1.41	1.23		1.03	0.92	0.91	0.78	1.31	
CH_3NO_2	1.25	1.09	0.97	0.99	0.91	0.91	0.82	1.09	
H_2O_2	--	--	--	0.695	--		--	--	
C_2H_2	1.83	1.54	1.08	1.15	1.03	1.00	0.83	1.24	
C_3H_4		1.45		1.10				1.22	

5. Whenever the possibility existed of forming either a metal hydroxide or metal oxide and water, the selection was based on that reaction resulting in the greatest $-\Delta F$ value.

6. In general, reactions among three or more chemical elements were evaluated by considering the various product possibilities, computing ΔF for each reaction prospect, and then choosing the one that gave the largest ΔF value for the evaluation of the standard free energy and enthalpy for the reaction.

Results tabulated in Tables 4-6 and 4-7 indicate that only beryllium, lithium, boron, their hydrides, and magnesium or alumimum were significantly superior to hydrogen from the energy standpoint. Of the oxidizers only ozone is consistently better than oxygen, but ozone can be dropped from further current consideration because up to the present time it has been difficult to prepare in concentrated form due to its explosive nature and it is toxic in a few parts per million. Fluorine and oxygen difluoride are generally superior to oxygen for the oxidation of the forementioned fuels.

Obviously, the preliminary screening on a thermodynamic basis can only act as a guide to the selection of the best fuel-oxidant combination. Other factors such as storage tank weights, conversion methods and efficiencies, availability, and practical considerations which can only be appreciated from a system study have to be assessed before the final selection can be made.

5.0 POWER SYSTEM STUDIES

Various mechanisms considered for the conversion of chemical energy to an electrical form may be generally classified as follows:

1. Gas expansion engines
    - Positive displacement
    - Turboelectric
    - Combinations of the above
2. Electrochemical generators
3. Thermoelectric generators
4. Thermionic generators
5. Photoelectric generators
6. Other possibilities based on magneto-fluid dynamic principles
7. Combinations of the above

Photoelectric generators are normally not applicable for chemical energy sources and will, therefore, be excluded from further consideration.

Thermoelectric generators are being developed for power levels up to 1 to 5 kilowatts, but their overall efficiency of 10 to 15% is rather low; consequently, they are being considered primarily for use with solar or nuclear energy or where excessive weight is not so great a factor as it is in satellites. The present rate of progress in materials research for improved efficiencies in thermoelectric generators makes a breakthrough unlikely in the immediate future. A major breakthrough is necessary before thermoelectric generators can be considered seriously for chemical energy sources.

Thermionic devices are relatively new concepts in power conversion. Converters in the watt power-level range have been made to study the parameters of this promising device. Thermal efficiencies up to 20% have been measured in some experimental models. Theoretical analysis indicates that efficiencies up to 40% may be possible. The device operates in a relatively high temperature range (2000°to 5000°R) and thus may be used as a topping unit in series with gas expansion engines or thermoelectric generators, both of which are forced by present materials restrictions to operate near the lower limit of the thermionic converter. The thermionic converter also has the possibility of being one of the lightest converters (pounds/kilowatt output) yet conceived. Used in series with gas expansion engines which might be considered for space, it would not only add its energy output to the output of the mechanical unit, thus increasing the overall efficiency, but at the same time would help solve the limiting-temperature problems which generally result in an additional weight penalty for mechanical engines. Although thermionic converters show considerable promise, the state of the art is not sufficiently advanced to consider them seriously at this time.

Other converters based on magneto-fluid dynamics principles are in the very early phases of research and development, but there is not enough information at present to estimate their potential value for the proposed application. While intensive research and development activities are proceeding at a vigorous rate on various types of converters, the ones considered in the study were limited primarily to gas expansion engines, which have a long proven history, and to electrochemical generators (or more specifically, fuel cells) which, although not firmly established, show promise of yielding efficiencies much higher than those of any other known converter.

5.1 SYSTEM STUDIES

The system studies considered all chemical system possibilities that would result in a system of minimum weight and maximum reliability regardless of their ability to produce by-products useful to man. Preliminary analysis of all chemical prospects indicated that the H_2-O_2 system was one of the best possibilities. It was the first system studied and was subsequently used as a standard for comparison when considering other chemical systems. A summary of the pertinent results of the analysis of the H_2-O_2 system is presented below. Details of the subsystem studies required for this system are presented in Appendices VII and VIII. In many respects this system is ideal from the viewpoint of meeting occupant requirements.

5.1.1 Hydrogen-Oxygen System

Selection of the H_2-O_2 system was based on the following factors:

1. Its high-energy content per pound of chemicals is exceeded by relatively few other possibilities.
2. It forms water, an important consideration as the water supply (approximately 6 pounds/day) involves the greatest weight factor in supplying the occupant's requirements.
3. Molecular oxygen may be supplied to the environmental atmosphere with a minimum of auxiliary equipment and maximum reliability.
4. The system is non-toxic; the only dangers involved are explosion hazards. (The explosive limits of hydrogen in oxygen are between 4 and 94%)
5. The reactants and products are all fluids and therefore may be handled with relative ease in a continuous process.
6. When the gases are stored in cryogenic form they provide a very effective (Btu/pound) heat sink which may aid in temperature control.
7. The system is readily adaptable to both gas expansion engines and electrochemical conversion methods for generating power, the latter method having demonstrated high efficiencies.

As the H_2-O_2 system appeared to supply as much to the occupant's environmental requirements as most systems that could be considered, attention was focused on its power-producing ability. This was analyzed both for gas expansion engines and electrochemical systems.

Gas Expansion Cycles

The object of the study was to arrive at a specific fuel consumption and system weight considering various types of gas expansion engines and cycles. Thorough coverage of the area was a large undertaking and attention had to be restricted to the most important or promising approaches. Both piston expanders and turbine systems were considered in two-stage systems. A third system, combining both piston expanders and turbine and utilizing each under its most favorable operating conditions, was also analyzed. The analysis was based on the largest power level anticipated, namely 10 kilowatts. If the mechanical engine system weight had proved inferior to hydroxy fuel cell system weights at this level, the conclusion would not likely be reversed at lower power levels.

Table 5-1 is a concise summary of the conditions considered and the results obtained. Additional details will be found in Appendix VII.

The results summarized in Table 5-1 were used to compute the total system weights as a function of mission duration. These are shown as part of Figure 5-1. The water-cooled piston engine yielded the lowest system weight over most of the duration at the 10-kilowatt level. System weights were computed for space radiators weighing 1 pound and 2 pounds/square foot. (The higher specific weight considers possible meteorite puncture.) Exhaust steam required for necessary dilution was condensed, and the remainder was ejected into space. The substitution of hydrogen, carried on board, to replace the condenser was considered. As Figure 5-1 shows, this may result in the lowest system weights for durations up to 2 days.

It will be noted that the SFC for the piston engine (1.23 pounds/kilowatt-hour) corresponds to a thermal efficiency (based on heating value of fuel) of 41%. This value approaches those recently publicized (40-45%) for the Phillips, Allison, or Sterling engine and may be considered within the present state of the art.

Electrochemical Conversion

Combination of hydrogen and oxygen through an electrochemical mechanism has been a goal long sought by electrochemists to circumvent some of the problems and limitations of heat engines. In the last few years the development of such cells, commonly known as hydroxy cells, has reached a point where they merit serious consideration for the size power unit being considered here. Three basic types of cells are generally recognized in this area:

1. Bacon cell (also known as Patterson Moos or porous nickel cell)
2. National Carbon cell (porous carbon electrodes)
3. Ion-membrane cell (or General Electric cell)

The basic reaction taking place is the same in all three cells. The reactions differ only in the nature of the electrodes and electrolyte. In all three types the hydrogen and oxygen gases are fed through porous electrodes to form water in the cell with the generation of approximately 1 volt open circuit. High efficiencies (40 to 80% of the theoretical) are possible; the highest efficiencies are obtained with low loads (or low current densities). Other general characteristics as well as differences among the three basic types may be obtained from Table 5-2.

TABLE 5-1

SUMMARY OF GAS EXPANDER CYCLES

Piston Engine, Two Stages, Hydrogen Diluent

	First Expander	Second Expander
Inlet Pressure	1000 Psia	100 Psia
Exit Pressure	100 Psia	10 Psia
Inlet Temperature	2060°R	2060°R
Power Output	7.83 Hp	7.83 Hp
Frictional Loss	0.40 Hp	1.86 Hp
Speed	8000 Rpm	8000 Rpm
Bore	1.25 Inches	2.15 Inches
Stroke	1.125 Inches	1.93 Inches
	1.04 Lb/hp-hr =	1.40 Lb/kw-hr

Fixed Engine Weights:

Piston engine	8.4 Lb
Combustors and fuel valves	10
Generator	25
Additional accessories	16.3
Total	59.7

Fuel Storage - Cryogenic
Total system weight versus duration - Figure 5-1

Piston Engine, Two Stages, Water Diluent

	First Expander	Second Expander
Inlet Pressure	1000 Psia	100 Psia
Exit Pressure	100 Psia	10 Psia
Inlet Temperature	2060°R	2060°R
Power Output	7.76 Hp	8.37 Hp
Frictional Loss	0.44 Hp	2.28 Hp
Speed	8000 Rpm	8000 Rpm
Bore	1.353 Inches	2.200 Inches
Stroke	1.217 Inches	1.980 Inches
SFC	0.922 Lb/hp-hr =	(1.235 Lb/kw-hr

Fixed Engine Weights:

Piston engine	9.4 Lb
Combustors and fuel valves	10
Generator	25
Water pump	10
Additional accessories	16.3
Total	70.7

Space Radiator @ 1 Lb/ft^2	147
Space Radiator @ 2 Lb/ft^2	294

Fuel Storage - Cryogenic
Total system weight versus duration - Figure 5-1

TABLE 5-1 (Continued)

SUMMARY OF GAS EXPANDER CYCLES

Turbine, Two-Pass Re-entry, Hydrogen Diluent

	First Pass	Second Pass
Inlet Pressure	500 Psia	10 Psia
Exit Pressure	10 Psia	1 Psia
Inlet Temperature	2060°R	1783°R
Power Output	5.4 kw	4.6 kw
Speed	60,000 Rpm	60,000 Rpm
Pitch Diameter	4.58 Inches	4.58 Inches
Blade Height	0.15 Inch	0.15 Inch
SFC	2.1 Lb/hp-hr = 2.82 Lb/kw-hr	

Fixed Engine Weight:

Turbine	10.5 Lb
Gear Box	20
Combustor and Valves	5
Generator	25
Additional Accessories	16.3
Total	76.8 Lb

Fuel Storage – Cryogenic
Total system weight versus duration – Figure 5-1

Piston and Turbine Combination, Hydrogen Diluent

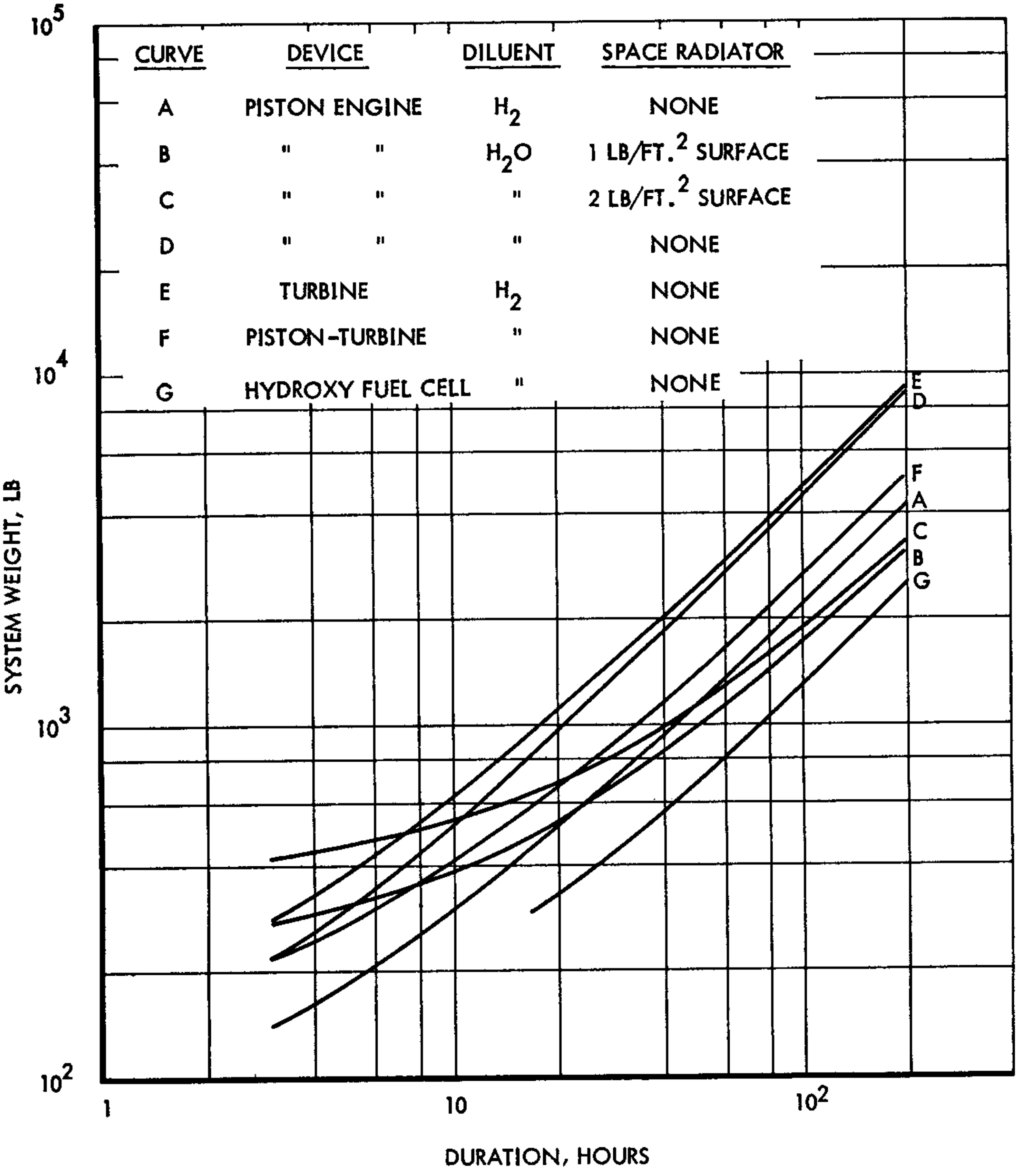
	Piston Engine	Turbine
Inlet Pressure	500 Psia	5 Psia
Exit Pressure	5 Psia	1 Psia
Inlet Temperature	2060°R	2060°R
Bore	2.55 Inches	4.58 Inch Pitch Diameter
Stroke	2.3 Inches	0.3 Inch Blade Height
Speed	5000 Rpm	60,000 Rpm
SFC	1.27 Lb/hp-hr = 1.70 Lb/kw-hr	

Fixed Engine Weight:

Piston Engine	14.8 Lb
Turbine	12.0
Gear Box	23.0
Generator	25.0
Combustor and Valves	10.0
Additional Accessories	16.3
Total	101 Lb

Fuel Storage – Cryogenic
Total system weight versus duration – Figure 5-1

SYSTEM WEIGHTS FOR 10-KW POWER RATING



CURVE	DEVICE	DILUENT	SPACE RADIATOR
A	PISTON ENGINE	H_2	NONE
B	" "	H_2O	1 LB/FT.^{2} SURFACE
C	" "	"	2 LB/FT.^{2} SURFACE
D	" "	"	NONE
E	TURBINE	H_2	NONE
F	PISTON-TURBINE	"	NONE
G	HYDROXY FUEL CELL	"	NONE

FIGURE 5-1

TABLE 5-2

HYDROXY FUEL CELL CHARACTERISTICS

Characteristics	National Carbon Co.	National R & D Corp. of Great Britain (Bacon Cell) and Patterson-Moos Div., Universal Winding Co.	General Electric Ion Membrane Cell
Hydrogen Gas Electrode	Porous carbon and metal catalyst	Porous sintered nickel	Nickel grid and Pt black
Oxygen (Air) Gas Electrode	Porous carbon and metal catalyst	Porous sintered nickel and lithiated nickel oxide	Nickel grid and Pt black
Electrolyte	55% KOH	27% KOH	Cation-Exchange Membrane
Operating Temperature, °C	50-60	200-240	20-100
Operating Pressure, atm	1-5	40-53	1
Open Circuit Voltage, v	0.95 - 1.02	1.1	1.08
Operating Voltage, v	0.95 - 0.6	1.0 - 0.6	1.0 - 0.6
Current Densities, A/ft^2	90 - 450	30 - 1000	3 - 45
Power/weight, w/lb	2 -3	15 - 20	10 - 20
Power/volume, w/ft^3	200 - 300	2000	150 - 1000
Operational Life	Thousands of hours	1500	Unknown
Energy Efficiency, %	65 - 70	Up to 80	Up to 75
Starting Time	Short	Long	Very short

While a detailed discussion of each cell is unwarranted at this point, it should be pointed out that the Bacon cell was chosen as the best suited for this study. National Carbon's cell is heavier and bulkier and not as shock and vibration resistant as the Bacon cell. General Electric's ion-membrane cell is still in its infancy, the tabulated data representing largely projected performance on the basis of very small experimental models. Furthermore, although no claims have yet been made about its expected life, the cation membrane by nature may be more susceptible to deterioration due to its sensitivity to elevated temperatures and moisture content. Obviously new developments could affect the selection at any time.

Weight analysis of the hydroxy fuel cell total system using the Bacon cell was based on the voltage-current density curves and typical generator weight breakdown reported by Alexander, Moos, Rapp and Sommer (Ref. 25). The voltage-current density curve for an operating temperature of 240°C is reproduced as part of Figure 5-2. The pertinent weight breakdown data are presented in Appendix IX.

The object of the calculations was to find the minimum weight of the system operating at 1 and 10-kilowatt power levels for durations of 1, 2, 6 and 10 days. The generator was to produce 28 volts. Cryogenic hydrogen and oxygen storage was used. Because of the importance of container weight, a subsystem analysis of cryogenic storage was made and is presented in Appendix VIII. The total system weight includes:

a. Cell weight
b. Accessories for cell
c. Cryogenic hydrogen storage weight
d. Cryogenic oxygen storage weight
e. Accessories for cryogenic tanks

Items b and e were assumed constant for a given power level. Items a, c and d are dependent on the loading of the cell. A high current density results in a low cell weight but high gas consumption; low current densities result in large cells but minimize the gas consumption. The relative importance of each weight will depend on the duration. Thus the minimum total weight was established as a function of current density and duration for both 1 and 10-kilowatt power levels. Details are summarized in Appendix IX. Parameters of interest obtained in the analysis are plotted against current density in Figure 5-2. This includes cell voltage, specific fuel consumption, cell weight, pounds of oxygen required/day, and pounds of hydrogen required/day. The optimum cell weight was found to be 11 pounds/kilowatt hour and proved to be relatively insensitive to current loading (above 100 ASF)* and duration. The optimum cell weight drifts slowly toward higher values for large fuel consumption; i.e., high power and long durations. The optimum specific fuel consumption is also relatively insensitive to cell loading above 100 ASF, having a value of about 0.97 pound/kilowatt-hour. It tends to drift to lower values for longer durations. The results are summarized in Table 5-3.

---

*ASF - Amperes per square foot

HYDROXY FUEL CELL CHARACTERISTICS VS CURRENT DENSITY

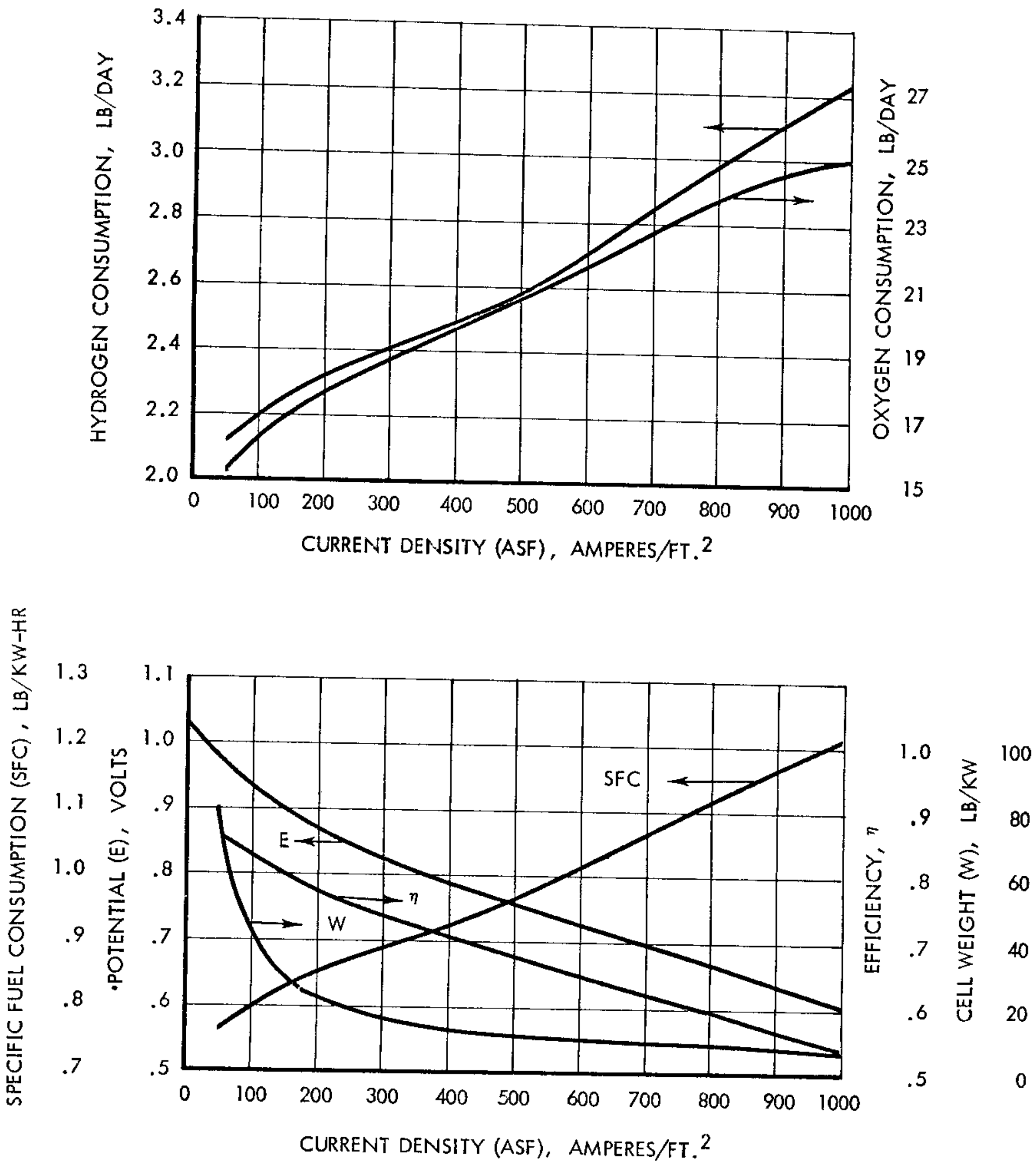


FIGURE 5-2

TABLE 5-3

HYDROXY FUEL CELL SYSTEM WEIGHTS

Duration	A, Lb	B, Lb	C, Lb	D, Lb	E, Lb	Minimum Total Weight	Watt-hour/Lb
				1 Kilowatt			
1 day	11	30	12.1	26.5	16	95	250
2 days	11	30	20.6	51	16	126	380
6 days	11	30	49.5	143.5	16	246	585
10 days	11	30	75	234	16	366	655
				10 Kilowatts			
1 day	110	50	70	236	20	386	620
2 days	110	50	121	456	20	657	730
6 days	110	50	335	1330	20	1845	780
10 days	110	50	534	2215	20	2929	820

Total system weight for the 10-kilowatt level was plotted against duration (Figure 5-1) to compare it with gas expansion systems. The hydroxy fuel cell system is definitely superior to the mechanical engine systems considered for all durations between 1 and 10 days. This conclusion is not likely to be any different so long as the bulk of the system weight is fuel. At the one-kilowatt level even if the hardware weight of the piston engine (A), of Table 5-1, were 10 pounds lighter than the fuel cell hardware, the advantage would be overcome in less than two days due to savings in fuel and accompanying tank weights.

In appraising the preceding results, generalizations that imply gas expansion engines are ruled out for future consideration must be avoided. The analyses for these cycles were limited and no effort was made toward optimization. Thus, judging from the overall efficiencies obtained, those cycles that have been examined may be considered typical of the present state of the art. Multistaging (using reheat and heat recovery), use of other working fluids, and other heat sources are some of the areas in which future improvements in performance may be expected.

The hydrogen-oxygen system was examined most thoroughly for reasons already presented. However, weight analyses were also made on several other systems, selected either because they had markedly higher energy values or because they offered the prospect of reducing total system weights through storage-container weight savings. These prospects are summarized in the following paragraphs.

5.1.2 Hydrocarbons-Oxygen Systems

Considering the relatively poor specific volume of cryogenic hydrogen and the relatively heavy container required to hold it (either for reasons of insulation or pressure) it seemed that the substitution of a liquid hydrocarbon as the fuel source might offer a weight savings in spite of its lower heating value. Thus C_8H_{18} and cryogenic oxygen were considered. Since all members of the paraffinic hydrocarbon that might be considered yield practically the same energy, the results are applicable to all.

The weight analysis was made under the following conditions: cryogenic oxygen was used as the oxidant; durations of 1, 6, and 10 days were considered at 1-and 10-kilowatt power level; an overall efficiency of 65% of ΔF for the reaction was assumed in making the estimates. This is typical of experimental fuel cells operating with hydrocarbons. The oxygen system weights were obtained for the cryogenic study (Appendix VIII), and a factor of 1.05 was used from the hydrocarbon system weights to allow for tank, pump, and miscellaneous hardware.

Identical hardware weights were assumed for the converters and accessories at either efficiency. This was 43 pounds for 1 kilowatt, and 160 pounds for 10 kilowatts, and was based on the hydroxy fuel cell weight. The results, summarized in Table 5-4, may be compared to total weights of the cryogenic hydrogen-oxygen system presented in the last column.

TABLE 5-4

PARAFFINIC HYDROCARBONS/CRYOGENIC OXYGEN SYSTEMS WEIGHTS

ΔF = 1.3 kw-hr/Lb; 65% efficiency ($\cong$ 1.85 Lb/kw-hr) assumed

Duration, Days	Weight of O_2 System	Weight of H/C System	Converter Weight	Total	Cryogenic H_2-O_2 System Weight
		1 Kilowatt Power Level			
1	36 Lb	6.6 Lb	43 Lb	86 Lb	95 Lb
6	161	40	43	244	246
10	258	66	43	367	366
		10 Kilowatts Power Level			
1	258	66	160	484	386
6	1438	400	160	1998	1845
10	2378	660	160	3198	2929

It will be noted that the total system weights for the hydrocarbon system are practically identical to the H_2-O_2 system at the 1-kilowatt power level, but the higher energy content of H_2-O_2 systems makes itself felt at higher power levels to favor this system. No consideration was given to the gas expansion cycles for the hydrocarbon-oxygen system since the 40% overall efficiency that would have to be assumed would make these system weights obviously inferior to those cited above. Converter system weights may be considered comparable to fuel cell systems weights.

In view of the similarity of the two chemical fuel systems at the lower power levels, some thought was given to the use of the hydrocarbon system as it eliminates the handling problems associated with cryogenic hydrogen. We concluded that the type of fuel cell required for the hydrocarbon fuel has not yet attained the developmental status of the hydroxy cell. There are several organizations doing research and development work in the hydrocarbon type of fuel cell. Within two to four years a hydrocarbon fuel cell, using liquid hydrocarbon fuels, that is comparable to the present developmental type of hydroxy cell in compactness and weight may be developed.

5.1.3 Metal Hydrides - Oxygen Systems

Other chemical fuel systems considered were the borane-type fuels and metal hydrides summarized in Table 4-1. These fuels were considered primarily as a source of hydrogen for the hydroxy cell. With the possible exception of LiH these systems yield more water than needed for the hydrogen generator. In addition, the products from the chemical systems containing lithium can be used, at least in theory, to remove CO_2. Thus, they appeared attractive. From the power production viewpoint, they offered the possibility of obtaining more energy per pound of fuel than could be obtained from the hydrogen-oxygen system. The reason is twofold: (1) considerable heat is evolved in the generation of hydrogen from these compounds so that if a thermal engine is used to extract the energy available from the hydrogen generator, the energy thus extracted may be added to that obtained from the hydroxy fuel cell that uses the hydrogen (and oxygen); (2) if these compounds are regarded as hydrogen storage systems, it becomes evident in comparing the weight of chemical per pound of available hydrogen with cryogenic hydrogen storage weight-ratio (tank weight + gas weight/pound gas) that some of these compounds offer weight savings for missions of short durations and/or low power levels when cryogenic weight ratios are high.

A summary of the best hydrides available from the systems weight viewpoint is presented in Table 5-5 which shows the reaction assumed to be taking place in the hydrogen generator and which was the basis of the computations. Also shown in the table are densities, the weight ratio, the heat evolved in the generator, and the energy available from a heat engine that might be used to convert this heat to mechanical or electrical energy. The power output for the engine is expressed in kilowatt-hour/kilowatt-hour of energy derived from the hydroxy cell used in conjunction with the engine. (The cell output is based on 1 kilowatt-hour/0.1082 pound H_2, or 1035 watt-hour/pound H_2O as used throughout this entire report.) Two heat engine overall thermal efficiencies, 20% and 40%, were considered. The latter may be considered the limit of the present state of the

TABLE 5-5

ENERGY AVAILABLE FROM HYDROGEN GENERATOR

H_2 Generator Reaction	Density of Hydride, Lb/ft^3	Weight Ratio, Compound/ Hydrogen	Heat Evolved Kw-hr/Lb H_2	Thermal Engine Power Output, Kw-hr/Kw-hr Hydroxy Cell Output. Assumed Engine Thermal Efficiency	
				20%	40%
$B_2H_6 + 3H_2O \rightarrow B_2O_3 + 6H_2$	27.8	2.31	4.4	0.1	0.19
$2B_5H_9 + 15H_2O \rightarrow 5B_2O_3 + 24H_2$	38.2	2.65	5.36	0.11	0.23
$B_{10}H_{14} + 15H_2O \rightarrow 5B_2O_3 + 22H_2$	48.6	2.78	5.65	0.12	0.24
$2LiBH_4 + 5H_2O \rightarrow 2LiOH + B_2O_3 + 8H_2$	41	2.70	3.28	0.07	0.14
$2Al(BH_4)_3 + 12H_2O \rightarrow Al_2O_3 + 3B_2O_3 + 24H_2$	33.8	2.98	3.75	0.08	0.15
$LiH + H_2O \rightarrow LiOH + H_2$	48.6	4.0	7.05	0.15	0.30
$2LiAlH_4 + 5H_2O \rightarrow 2LiOH + Al_2O_3 + 8H_2$	57.2	4.75	4.1	0.09	0.18

art as indicated previously, while the former would be a very respectable estimate considering some of the heat-recovery problems of the hydrogen generators.

On the basis of the above reactions, total power system weights were calculated for each of the above compounds with (1) no energy recovery attempted in the hydrogen generator, (2) thermal energy available from the generator recovered with 20% overall efficiency, and (3) thermal energy available from the generator recovered with 40% efficiency. Two combined outputs of 1-and 10-kilowatt power levels were considered with mission durations of 1, 5, and 10 days.

The bases for estimating the fuel cell and accessories weights as well as for estimating cryogenic oxygen storage tank and accessories weights were consistent with those used in the analysis of the H_2-O_2 system. Container weights for all hydrides except B_2H_6 were based on the use of a single shell of Ti6Al4V, at 800 psia operating pressure, same design stress (107,000 psia), and same minimum thickness restrictions (1/16 inch). Diborane, in view of its low boiling point (-92°C), was considered as a cryogenic fluid and container weight was adjusted accordingly.

For the sake of simplifying the weight analysis, no distinction was made between using the container as a storage tank or as a generator. A 100% increase in container volume over that computed from the densities listed in Table 5-5 was allowed to take care of 50% void volume when using solid hydrides like LiH, or 50% increase in weight when using liquid hydrides to allow for reaction chamber, pump weights, etc. In any case these container or generator weights for the hydrides proved to be a small fraction of the total systems weights so that variations from the above assumptions would have a negligible effect on the results. The mechanical engine system weight assumed for the size engines being considered was 40 pounds/kilowatt output from the engine. This is comparable to engine weights used elsewhere in the study.

On the basis of the above conditions and assumptions, the total system weights [i.e., hydrides + container (H_2 generator), engine, hydroxy cell + accessories, and cryogenic oxygen system] were calculated for each compound and are presented in Table 5-6. Cryogenic hydrogen and oxygen is included for comparison.

Keeping in mind the restrictions and assumptions made in arriving at weights shown in Table 5-6, it may be concluded that without the extraction of some power from the heat released in the hydrogen generator, the superiority of any of the hydride systems versus cryogenic hydrogen is debatable at 1-to 10-kilowatt power level and 1 to 10 days. Any weight advantage hydride systems may have over hydrogen without such extraction is most noticeable at low power levels and duration where the cryogenic hydrogen weight ratios are relatively high due to minimum thickness restrictions for the container wall thickness and the relatively large specific volume of cryogenic hydrogen. With the conversion of 20% of the heat released from the hydrogen generator it may be possible to realize up to 10% savings in weight using hydrides at 1-kilowatt power level and 1 to 5 days duration. Considering the additional complexity of the system (addition of the H_2 generator and engine), the advantage of the hypothetical weight saved when using any of the hydrides

TABLE 5-6

SUMMARY OF TOTAL POWER-SYSTEM WEIGHTS FOR METAL HYDRIDE-OXYGEN SYSTEMS USED IN COMBINED THERMAL ENGINE + HYDROXY CELL* CYCLES

	1 day			5 days			10 days		
At 1-Kw Total Power									
Engine Efficiency	0%	20%	40%	0%	20%	40%	0%	20%	40%
B_2H_6	96	91	87	230	213	196	389	357	330
B_5H_9; $B_{10}H_{14}$	92	87	79	222	204	185	376	342	310
$LiBH_4$	92	89	86	222	213	200	378	358	336
$Al(BH_4)_3$	94	90	86	228	215	202	388	363	341
LiH	97	91	84	241	216	195	414	367	328
$LiAlH_4$	100	98	91	251	237	218	434	405	374
H_2 (cryogenic)	95			221			366		
At 10-Kw Total Power									
B_2H_6	414	410	410	1716	1590	1500	3132	2880	2700
B_5H_9; $B_{10}H_{14}$	401	400	400	1682	1540	1440	3200	2900	2660
$LiBH_4$	403	403	402	1690	1600	1530	3218	3040	2870
$Al(BH_4)_3$	413	413	410	1741	1650	1560	3318	3120	2930
LiH	409	408	406	1865	1680	1530	3573	3160	2840
$LiAlH_4$	459	455	450	1968	1840	1730	4307	3980	3720
H_2 (cryogenic)	386			1560			2929		

*Fuel cell output assumed: 1035 watt-hours/pound H_2-O_2

under these conditions is marginal. The weight advantage that any of the hydrides may have at 20% engine efficiency and 10-kilowatt total power over cryogenic hydrogen has for all intents and purposes disappeared.

At 40% engine efficiency and 1 kilowatt-hour/pound H_2-O_2 hydroxy cell output, the advantage of the hydrides over hydrogen is more obvious, especially at the lower power levels; however, it is debatable that such efficiencies can be achieved with the systems at hand. Although no mention has been made of the practical aspects of the hydrogen generator using hydrides, the compact and lightweight unit assumed in the estimates remains to be developed. It is not known, for example, what conditions are necessary to achieve the 100% completion of the reactions as assumed in these estimates. Of the various hydrides considered, pentaborane and decaborane generally result in the lowest system weights. These materials are also highly toxic.

Weight advantages of the hydrides over cryogenic hydrogen in the hydride-oxygen system are favorable only with the addition of a heat engine to the fuel cell of the power cycle. This complicates the system considerably. In view of the relatively small gains in weight savings possible, the assumptions made in the calculations, the uncertainties in hydrogen generator performance, and the toxicity of some of the more promising hydrides, the use of such systems is not recommended at this time.

5.1.4 Miscellaneous Chemical Systems

Hydrogen Peroxide (H_2O_2)

Attractive because it readily yields power, oxygen, and water, this substance was examined only superficially since, for all systems where power system weights predominate, H_2O_2 is obviously inferior to the H_2-O_2 system. Using even a 40% thermally efficient engine, the power output is 280 watts/pound H_2O_2 or 86 pounds H_2O_2/day without considering hardware weights. Allowing a factor of 1.1 for the container and catalytic chamber weight and 40 pounds/kilowatt for the engine unit brings the total up to 134 pounds for 1 day versus 95 pounds for the H_2-O_2 system. For a five-day mission the values are 510 pounds for H_2O_2 versus 221 pounds for the H_2-O_2 system. Thus unless the power levels are much less than 1 kilowatt and/or the durations are less than one day the hydrogen peroxide system would have to be ruled out in spite of its simplicity.

High Energy Chemical Systems Supplying No Useful By-products, e.g., Be-LOX and Li-Liquid Fluorine

These two systems must be regarded as high-energy heat sources at the present time as no electrochemical cell systems have been devised to extract their high-energy content. Assuming an overall engine efficiency of 32%, the total system weights to supply power and water (6 pounds/day of water carried on board as such) is given in Table 5-7. Cryogenic H_2-O_2 is included for comparison.

TABLE 5-7

TOTAL SYSTEM WEIGHTS FOR Li-F_2 AND Be-O_2 POWER SYSTEMS USING 32% EFFICIENT HEAT ENGINE

		Duration, Days		
		1	5	10
1 Kilowatt				
Li + F_2	(cryogenic storage)	88	228	409
Be + O_2	(cryogenic storage)	86	224	395
H_2+ O_2	(cryogenic storage)	95*	221*	366*
10 Kilowatts				
Li + F_2	(cryogenic storage)	495	1615	3010
Be + O_2	(cryogenic storage)	449	1550	2880
H_2 + O_2	(cryogenic storage)	386*	1560*	2929*

*Using hydroxy cell with 1035 watt-hour/pound H_2-O_2 output.

Most of the time Li + F_2 and Be-O_2 systems are comparable to the H_2-O_2 system at the relative efficiencies considered. The 32% efficiency assumed for those systems containing solid reaction products, although not so high as those assumed previously, is considered realistic in view of the difficulties that would be involved in extracting the heat from the above systems. In view of the above findings and the difficulties and danger in dealing with fluorine and beryllium, there is little incentive to examine the Be-O_2 and Li-F_2 systems for the proposed application at this time.

5.2 SUMMARY

The following chemical systems have been examined as a source of power and by-products useful to man:

1. Cryogenic hydrogen and cryogenic oxygen
2. Liquid paraffinic hydrocarbons and cryogenic oxygen
3. The borane type fuels with cryogenic oxygen
4. Metal hydrides ($LiBH_4$, $Al(BH_4)_3$, LiH, $LiAlH_4$) with cryogenic oxygen
5. Hydrogen peroxide
6. Beryllium - cryogenic oxygen; lithium and fluoride

The selection of any of these systems on a minimum weight basis depends almost entirely on the power level desired in the capsule and the mission duration.

Considering all pertinent factors, cryogenic hydrogen-oxygen chemical systems offer the most promise for durations of 1 to 10 days and power levels of 1 to 10 kilowatts. The selection is made on the following bases:

a. The cryogenic oxygen supply offers the lightest, and possibly most reliable, known source of pure oxygen for the occupant.

b. Water is formed as a by-product of the power unit, assuring the occupant an adequate supply at any power level over 250 watts.

c. The hydrogen-oxygen system has a high energy per pound and is exceeded by only a relatively few other chemical systems in this respect. The hydrogen-oxygen system is the only one of these high-energy systems for which a highly efficient generator (hydroxy cell) has been developed to convert the chemical energy into electrical. Thus the combination of high available energy and efficient converter produces as high an energy per pound as any known fuel system in most cases (power level and duration) considered.

d. The relatively large heat sink available in the cryogenic fluids will aid in controlling the internal temperature of the capsule.

e. The high fuel cell efficiency possible with the H_2-O_2 system decreases the heat load in the capsule.

f. The system is non-toxic. The only danger lies in the explosion hazard as a result of possible H_2 leakage from the system.

The potential advantage of using chemically produced hydrogen lies in the possibility of being able to use a second converter in series with the hydroxy cell to extract more energy per pound of fuel. This results in a much more complex system and uncertainties regarding the actual reaction mechanism. It was not considered worthwhile in the absence of more basic information.

As the power level and duration are decreased, the hardware weights rather than chemical weights become the controlling factor in the weight analysis. Thus system weights become difficult to evaluate at these levels without an accurate and detailed specification layout of the equipment involved and the selection of the best chemical system on a weight basis becomes more speculative.

6.0 PROTOTYPE DESIGN

Preliminary studies on the propellant-atmosphere system pointed to the cryogenic hydrogen and oxygen chemical system as the most suitable chemical system available for both environmental and power requirements. It can supply oxygen in readily available form, supply relatively pure by-product water with a minimum of equipment or energy, and furnish the means for cooling and dehumidifying the capsule atmosphere. The possibility also exists for freezing out CO_2 with the system, which would further enhance its value. Equally important, the cryogenic hydrogen-oxygen system proved to be the lightest system available to produce the power required. The system has one of the highest specific energies known and at least half of this potential energy can actually be realized by the hydroxy fuel cell converter. Since the efficiency of the conversion is about twice that of currently available thermo-engines, the combination of high intrinsic energy and high conversion efficiency makes the H_2-O_2 system unique as an electrical energy source.

On the basis of these advantages, permission was received from the Aerospace Medical Laboratory of WADD to proceed with a design prototype of a cryogenic hydrogen-oxygen system for missions up to three days' duration. Since preference was expressed for a portable or semi-portable system, the choice was narrowed to a system weighing about 150 to 200 pounds. Beyond these specifications the selection of both power level and duration for the prototype has been somewhat arbitrary.

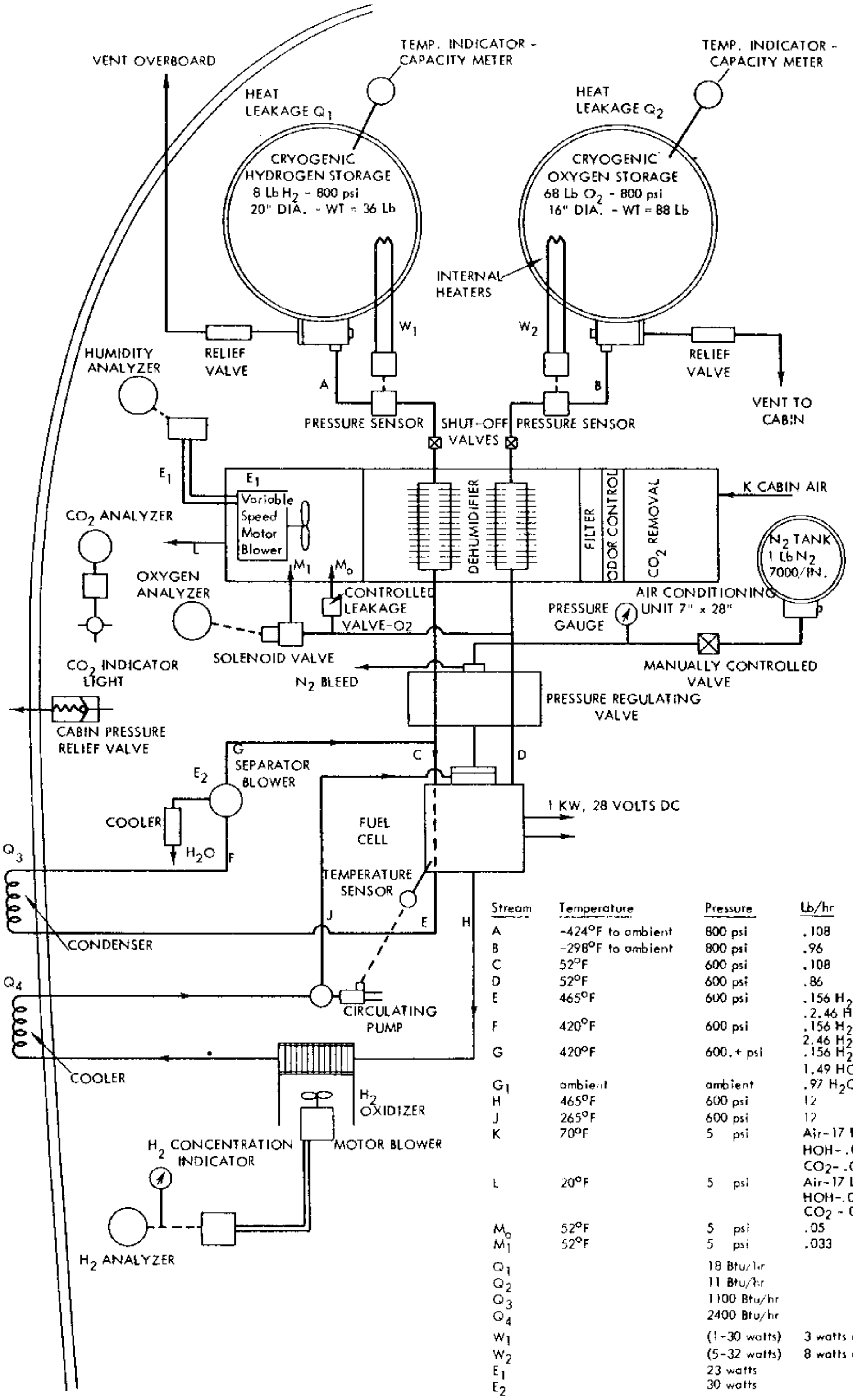
The power level chosen was one kilowatt. This is in line with many estimates made for the electrical power requirements of manned space capsules of the near future of advanced Mercury types. (Many estimates have also been made for a 10-to 30-kilowatt power unit and even greater. Presumably these will also be used for propulsion and possibly for control of glide vehicles.) The selection of any power level is of small consequence in a study design of this nature as long as it affects only the scale of the equipment and not the nature of the process. The one-kilowatt level chosen is large enough to permit dehumidification and consideration of CO_2 removal by freezing out.

A flow sheet of the layout of the propellant-atmosphere system is shown in Figure 6-1 and features two systems or streams, i.e., the environmental unit which purifies the cabin air, and the fuel cell power system through which the cryogenic fluids flow.

6.1 ENVIRONMENTAL ASPECTS OF THE SYSTEM

Cabin air (essentially oxygen at 70°F and 5 psia, containing CO_2 at less than 4 millimeters mercury partial pressure or approximately 1.5% and a relative humidity of 50%) is circulated through the environmental unit to remove CO_2, odors, water vapor, and suspended solids, in this order. The exit air, which has been stripped of these contaminants and cooled in the process, is led through a plastic casing. The air velocity issuing from the casing will also keep the air circulation in the cabin at satisfactory levels. Makeup oxygen is introduced at the end of the air conditioning section to distribute it uniformly in the cabin. Water for the occupant is obtained from the blower-separator in the power unit. Essentially all of the occupant's requirements except food may be derived from the system.

PROPELLANT - ATMOSPHERE SYSTEM SCHEMATIC



Stream	Temperature	Pressure	Lb/hr
A	-424°F to ambient	800 psi	.108
B	-298°F to ambient	800 psi	.96
C	52°F	600 psi	.108
D	52°F	600 psi	.86
E	465°F	600 psi	.156 H_2 .2.46 HOH
F	420°F	600 psi	.156 H_2 2.46 H_2O-HOH
G	420°F	600.+ psi	.156 H_2 1.49 HOH
G_1	ambient	ambient	.97 H_2O
H	465°F	600 psi	12
J	265°F	600 psi	12
K	70°F	5 psi	Air-17 Lb HOH-.008 Lb/Lb air CO_2-.006 Lb/Lb air
L	20°F	5 psi	Air-17 Lb HOH-.002 Lb/Lb air CO_2 - 0
M_o	52°F	5 psi	.05
M_1	52°F	5 psi	.033
Q_1		18 Btu/hr	
Q_2		11 Btu/hr	
Q_3		1100 Btu/hr	
Q_4		2400 Btu/hr	
W_1		(1-30 watts)	3 watts average
W_2		(5-32 watts)	8 watts average
E_1		23 watts	
E_2		30 watts	

FIGURE 6-1

Selection of LiOH for CO_2 removal represents the best solution for a one-man mission of three days' duration considering reliability, weight, and simplicity of the system. Other possibilities included freezing out with cryogenics, absorption with amines, adsorption with molecular sieves and KO_2. Freezing out resulted in a greater total systems weight than was estimated for a system using LiOH (see Appendix X). Use of KO_2 to remove CO_2, odors, and some water vapor and to generate O_2 proved to be considerably heavier than the environmental systems selected (see Appendix X and Section 3.0).

Dehumidification by heat exchange with cryogenics proved superior to any other method considered for this specific design, e.g., the use of Anhydrone, regenerative use of silica gel, or molecular sieves. (See Appendix VI.) Dehumidification was accomplished with a weight penalty of about 2 pounds for the heat exchanger. If we assume that the exchange would have been required anyway for utilization of the heat sink capabilities of the cryogenic fluids to cool the cabin air, we might argue that it was accomplished with no weight penalty at all. In either case we could hardly hope to improve on the weight, reliability, or simplicity of this system. The problem of moisture removal from the cabin air was even simpler than expected for less than a three man-day mission since the moisture could be allowed to accumulate on the exchanger surface without affecting the heat transfer rates significantly, be it present as water, ice, or snow. Removal of condensed moisture was also considered for a greater number of man-days than used in this design and a collapsible, light, and easily replaceable exchanger design was recommended for such cases. This may be an improvement over dual exchanger systems and other methods that might be suggested from the weight, volume, mechanical complexity, and possible water recovery viewpoint.

The oxygen source was dictated by the selection of the power system and coincided with the choice of cryogenic oxygen from the minimum weight viewpoint, even if supplied only for the environment. Other possibilities have already been discussed in previous sections. These possibilities are largely solutions to the problem viewed from the systems viewpoint, e.g., H_2O_2 and KO_2, and were eliminated after preliminary evaluation of the total system weight.

Reliability and less hazards were additional contributing factors leading to the selection of oxygen supplied in elemental form.

Odor control was accomplished by the use of 1-1/2 pounds of activated carbon for the three man-day mission. Considerable thought was given to the replacement of carbon with the same weight of KO_2 which, in addition to controlling the odor problem, potentially offered an additional safety factor in the oxygen supply, carbon dioxide, and moisture removal systems and at the same time might even oxidize traces of hydrogen that could leak out of the high pressure fuel cell system. However, KO_2 might be used up prematurely by appreciable percentages of CO_2 and water vapor that would be passing through the system at times, prohibiting its use for odor control. Pending the experimental evaluation of KO_2 for odor control and hydrogen oxidation under the expected operating conditions, we thought it advisable to rely on activated carbon for odor control and make special provisions for the removal of hydrogen traces.

Explosion hazards are a real threat with the leakage of hydrogen from the high pressure fuel cell system. Three to four percent concentration represents an explosive mixture. In spite of all precautions to minimize joints and seals, it would be unrealistic to assume that leakage could be completely eliminated. For example, a leakage rate of only 15 cubic centimeters/minute in a 100-cubic-foot capsule volume would accumulate to explosive concentrations in a three-day period. The problem is solved by heating part of the air to 400°F and passing it through a bed of special 1-1-1 catalyst (containing a few percent of cobalt oxide and traces of plutonium and palladium on an inert carrier) to oxidize the hydrogen. The electric heater and catalyst may be another component in the air conditioning unit or else can be attached to the power system with a separate blower, as shown in Figure 6-1. The latter method was chosen for its advantage of by-product heat from the fuel cell circuit to heat the air and thereby avoid electric power weight penalties. While the net savings in total systems weight is nil for the three-day mission because of the weight of an additional blower, the arrangement offers potential advantages for a longer mission, allows more flexibility in environmental controls, and may provide an additional blower which might conceivably be used to handle the entire environmental load if one motor-blower fails.

In the environmental unit, the LiOH bed should precede the dehumidifying section so that the moisture aids in increasing the capacity of LiOH for CO_2 as reported in Section 3.0. If tests prove that KO_2 would be more desirable than activated carbon for deodorizing, it should follow both the CO_2 and dehumidifying sections.

The first operational factor to be considered is the mass flow rate of air through the various sections of the system. Theoretically, to minimize power consumption each section should have mass flow rates of air computed for the load for that section. Since flow rates required for dehumidification are about 3 to 4 times those required for CO_2 removal, ports that allow part of the air to be dehumidified to by-pass the LiOH bed are inserted between the dehumidifying and CO_2 absorption sections. These side streams can be regulated and shut off completely by turning the band over the ports. This would force the entire air flow through the LiOH bed and since the maximum flow rates are set by the dehumidifier section, the CO_2 concentration could be decreased below the specified 4-millimeter mercury limit. This would not do any harm and might even prove beneficial.

It is anticipated that the motor-blower will be operating continuously to provide the air circulation desired in the cabin and to handle the minimum dehumidification and CO_2 loads. A variable speed motor controlled by the relative humidity sensor would be desirable for peak dehumidification loads. Oxygen, carbon dioxide, hydrogen, and relative humidity analyzers would be provided with visual indicators and provision for recording. When the CO_2 concentration exceeds 1.5% (i.e., 4 millimeters mercury) a red light would indicate that it is time to change canisters. (In the prototype design, provision has been made to replace these canisters. For practical purposes the entire LiOH required for the three man-day mission could be placed in the unit at the start; however, the weight penalty for power consumption can be reduced by 2 to 3 pounds by replacing the first canister after about 36 hours.)

Oxygen concentration is maintained automatically by solenoid control of valve B as shown in Figure 6-1. To improve reliability of the oxygen supply we by-passed most of the oxygen through a preset valve and relied on the solenoid valve only for demands above the basal rate (1.2 pounds/ day), thus assuring the occupant of an uninterrupted supply regardless of what may happen in the oxygen-analyzer-control circuit. Possible hydrogen contamination of the cabin air will be sensed by a hydrogen analyzer which will turn on the motor-blower for the device, sending air through the heated catalyst bed. The catalyst bed is heated with by-product heat derived from the fuel cell system.

The occupant will have a supply of oxygen and will not suffocate from excessive CO_2 concentration if the control elements of the system fail. In case of failure of the motor-blower in the air conditioning duct, several alternatives exist to remove CO_2: (1) The motor-blower of the hydrogen oxidizer unit could be placed in the air conditioning unit if it is not being used for H_2 removal; (2) The canisters containing LiOH may be composed of 1-inch-thick packs of LiOH contained by screens and in an emergency these may be distributed throughout the cabin and used with whatever air circulation is available. In addition to these safeguards that are available without any significant weight penalties, undoubtedly others may be provided by a space suit.

As a result of the above considerations the air conditioning unit shown in Figure 6-2 was designed. Additional details concerning it may be found in Appendix X.

6.2 FUEL CELL POWER SYSTEM

Major components of the fuel cell system are cryogenic containers and the hydroxy fuel cell. It also includes a cooler, condenser, and blower-separator needed for continuous operation of the fuel cell. As seen from the process flow sheet (Figure 6-1), the fuel cell circuit also provides by-product water for occupant use and by-product heat for the hydrogen oxidizer. This part of the propellant-atmosphere design may be described as follows: Cryogenic hydrogen and oxygen are maintained at a constant pressure of 800 psi in the tanks and are fed into the fuel cell by internal heaters (automatically controlled by pressure sensors) in the tanks which maintain both fluids above the critical point so that they are expelled as a single phase. The fluids, still far below ambient temperatures, pass through the heat exchangers (which are considered part of the environmental systems as they would not be needed otherwise) to a special pressure regulating valve and into the fuel cell where they combine to yield current at approximately 1 volt per unit cell and by-product, water.

In the fuel cell, hydrogen and oxygen gas diffuse through their respective electrodes, which are made of porous sintered nickel of controlled porosity, and after transfer of the electrical charge at the surface, combine to form water. The water dilutes the electrolyte on continued operation so that the internal resistance of the cell increases, thereby-decreasing its efficiency. Water may be removed by evaporation from the back surface of the electrodes (on the gas side) as long as the partial pressure of water vapor from the solution in the pores exceeds that in the fuel gases in the vicinity. Normally water may be removed by recirculation of either or both gas streams which are practically saturated

AIR CONDITIONING UNIT

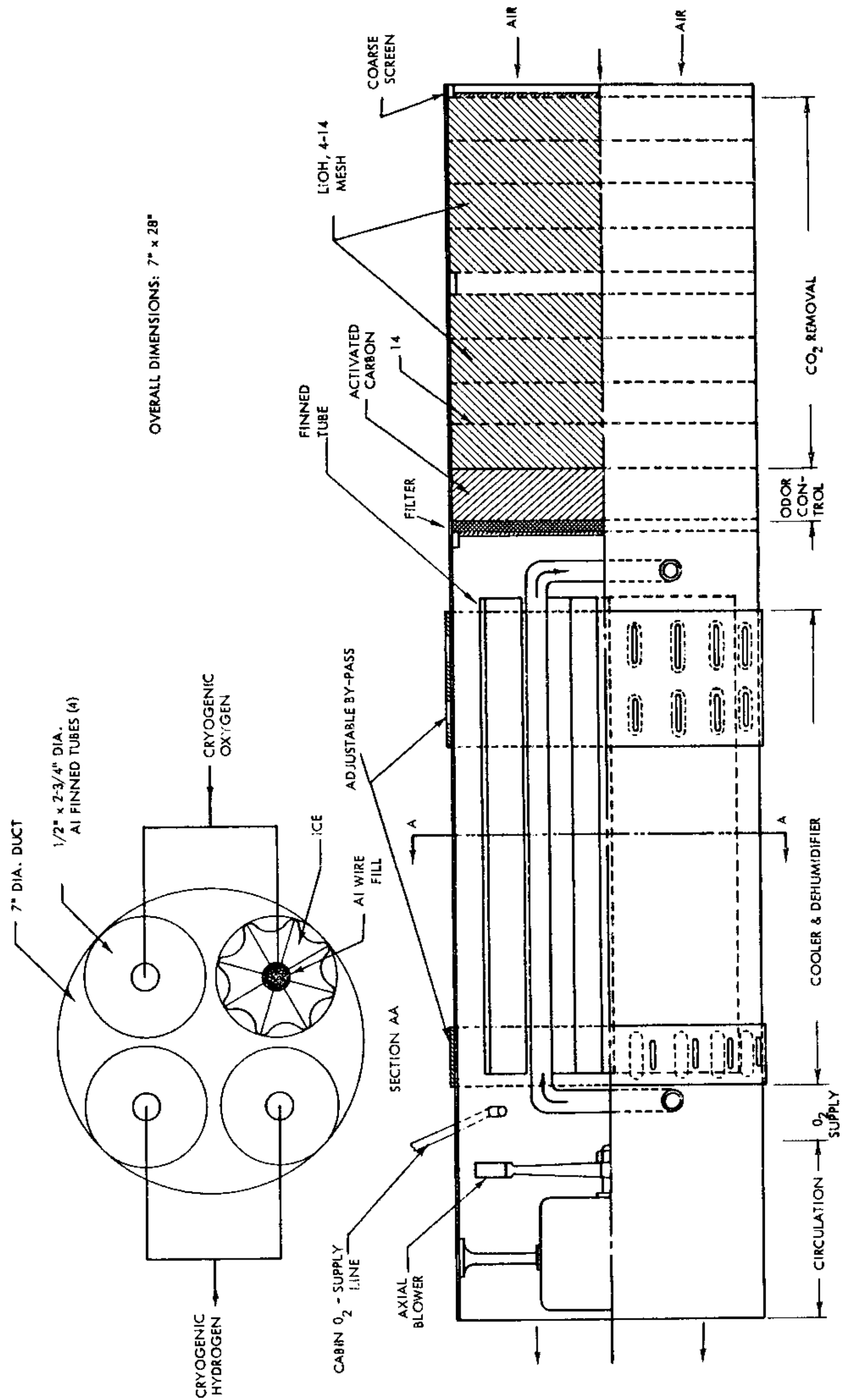


FIGURE 6-2

with water at the operating temperature and pressure (approximately 240°C and 600 psi) through a cooler-condenser. In this design we chose to remove water from the hydrogen side. In a gravity-free environment we are relying on shear forces in fluid flow and entrainment in the hydrogen loop to carry the condensed phase to a centrifugal separator where the phase separation occurs. As an integral part of the separator, an impeller restores the pressure drop suffered by the fluid as it recirculates in the loop. The collected water is forced out of the separator into a collector by the pressure differential between the inside and outside of the fuel cell system.

Heat, at the rate of about 3400 Btu/hour, has to be removed from the cell which requires additional cooling. Circulation of additional fluid in the hydrogen loop to handle the cooling load would remove water from the cell, at the desired electrolyte concentration, faster than it is being made. The arrangement shown in Figure 6-1 is only one means of handling the problem of independently controlling the rate of water removal and cooling. Another possibility would be to circulate the electrolyte and throttle it from 600 psi down to a lower pressure. The solution would then be cooled by evaporation and the resulting vapor would be sent to a condenser. The concentrated electrolyte would be pumped back into the cell.

There is one critical control problem relative to the operation of the fuel cell that is not readily evident at first glance. Because the electrodes are porous, the feed gases can bubble through the pores if the pressure differential between gas side and electrolyte exceeds 2 pounds. If the pressure difference between the hydrogen and oxygen side exceeds 4 pounds, the electrolyte and eventually the higher pressure gas will be forced into the lower pressure compartment. Either of these situations is very undesirable, the first because gas bubbles would isolate the activating areas and thereby increase the internal resistance; the second because blowing the electrolyte out would be tantamount to by-passing the cell and it would have to be shut down. The problem is solved by the use of pneumatic sensing equipment which references the feed gases to a static nitrogen head as originally suggested by Alexander, etc. (ref. 25), by means of the special pressure-regulating valve originally designed by Aro.

Necessary conditions for operation of the system are at all times equalization of the hydrogen and oxygen pressures and the maintenance of the differential pressure in the nitrogen system. The nitrogen pressure which is also transmitted to the electrolyte serves as a reference to the oxygen pressure as well as the hydrogen pressure. This obviates both the need for using two matched differential regulators for the feed gases and the probable variations of two matched components with time and operation.

6.3 COMPONENTS SUMMARY

The major components of the propellant-atmosphere system are: (1) an air conditioning unit, (2) cryogenic containers, (3) a fuel cell system consisting of a hydroxy cell, pressure regulating valve, water separator, cooler-condenser, and a nitrogen tank, and (4) analyzers. Rather extensive subsystem studies were necessary in air conditioning, cryogenic containers, and the hydroxy fuel cell to optimize the system. These are reported in detail in Appendices, so only the salient facts and conclusions will be reported here.

6.3.1 Air Conditioning Unit

The ultimate advantages of the cryogenic hydrogen-oxygen system would be realized if, in addition to dehumidification, CO_2 could be removed by freezing out. Since the power system requires the use of hydrogen-oxygen at high pressure, scrubbing of the cabin air by direct contact is out of the question and heat exchangers are necessary. Some analyses were made to determine feasibility in this area (see Appendix X).

With the use rate of cryogenics required for a one-kilowatt output fuel cell, the heat sink capacity is inadequate to supply the necessary cooling in countercurrent exchange with a minimum approach of 9°F (5°K). However, the heat balance requirements could be met within the one-kilowatt power system if an additional exchanger were used for the cold air leaving the hydrogen heat exchanger and the incoming air. A total of 34 square feet of exchanger area, however, is required for the system. Assuming the use of fins with a fin efficiency of 80% and an average weight of 0.425 pound/square foot (equivalent of an average fin thickness of 0.03-inch thickness of aluminum), the exchangers weigh 18 pounds. The total system weight (power plus environmental control) is three pounds heavier than the system using cryogenics for dehumidification and LiOH for CO_2 removal which was eventually selected.

A greater cryogenic use rate than that equivalent to one kilowatt would decrease the heat exchanger area and weight by permitting large temperature differences, so that it could have overtaken the alternate system within the mission duration. Likewise, a mission longer than 3 to 4 days would have given this method a weight advantage over that selected. The basic question is the reliability of the method in the face of possible large variations in use rates brought about by variable power loads. It is conceivable that at low power levels part of the CO_2 could evaporate back into the atmosphere. Removal of the CO_2 is another problem that would have to be faced eventually, if not within the three-day period. Because the nature of the solidified phase (compact solid versus frost) on the exchanger surface is not known, it cannot be estimated how long it would take the CO_2 on the exchanger to cut down the heat transfer significantly and make the rate of CO_2 removal less than the metabolic CO_2 rate. Since the maximum weight that could be saved for this particular system is essentially the weight of LiOH, or 8 pounds, there was very little incentive to pursue CO_2 freeze-out schemes further in this particular design. The scheme may be worth considering for manned missions that have larger CO_2 loads and larger cryogenics use rates than those considered here.

Using cryogenics for dehumidification only requires about 4 square feet of exchanger surface which weighs less than 2 pounds. The exchanger is built with longitudinal fins on the outside and packed with aluminum wire or small tubing on the inside for improved heat transfer. A tentative design is shown as part of Figure 6-2. The dehumidifier (and cooling) section consists of four finned tubes, 1/2 inch ID, with longitudinal fins 0.03 inch thick, 1 inch wide and 12 inches long. Since the exchanger areas of the oxygen and hydrogen streams are about the same, two tubes in parallel are used for each fluid. Air flows countercurrent to the cryogenic gas flow. The manner in which ice is expected to form on the fins is indicated in Section AA of Figure 6-2. The total surface

AIR CONDITIONING UNIT WITH COLLAPSIBLE AND REPLACEABLE DEHUMIDIFIER

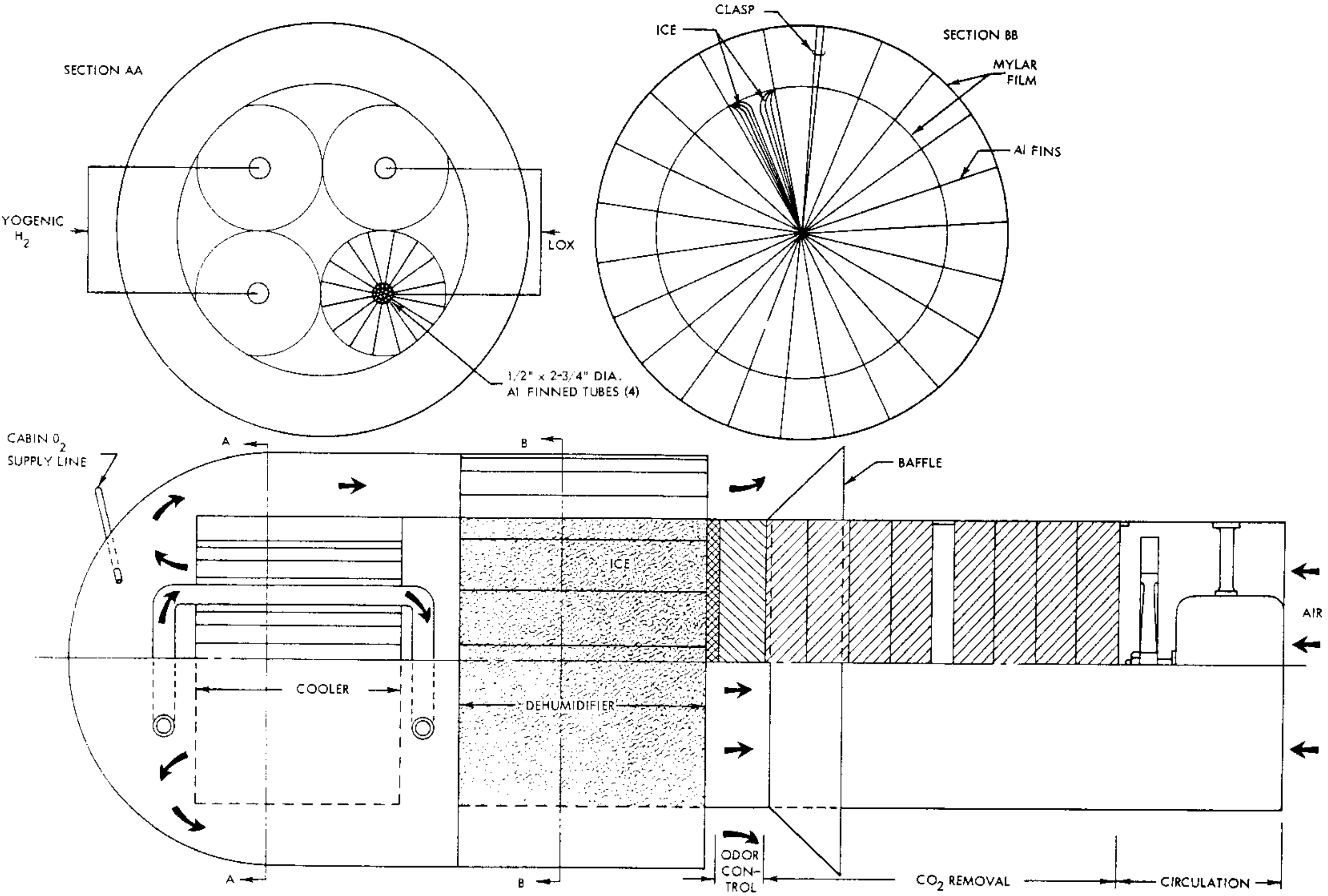


FIGURE 6-3

of the ice is still > 4 square feet and the bulk of the resistance to heat flow is still in the air stream so that the transfer rates toward the end of the mission should still be sufficient to handle the load. At the end of three days 7.5 pounds of water will have frozen on the fins. This is almost one gallon and the dehumidification section volume was made large enough so that at the end of three days the free cross-sectional area is still 50% of the total. Thus pressure drop should be insignificant at the air flow rates anticipated.

Two by-passes shown in the dehumidifying section are available at a very small weight penalty and permit considerable freedom in regulating the relative amount of air flowing through the different sections. The by-pass at the right determines the relative amount of air being dehumidified and of that passing through the CO_2 absorber. Since the relative quantities of air required for dehumidification are about 3 to 4 times that required for CO_2 removal, blower power reductions can be effected by the use of the by-pass. The by-pass at the left permits more air to be circulated about the cabin without all of it passing through the dehumidifier, thus maintaining the humidity and avoiding needless pressure drop losses.

The CO_2-removal and activated-carbon pack consists of approximately 4.5 pounds LiOH (4-14 mesh) and 0.75 pound activated carbon of a similar mesh size, enough for about 36 hours. They are replaced on indication of the warning light on the CO_2 analyzer. The LiOH pack is composed of eight 1-inch-thick sections. This gives more flexibility to the system without significantly increasing the weight. Each section is faced with 14-mesh screens and a variable number of sections may be placed in the train if pressure drop losses prove significant. In addition, the distribution of these sections about the cabin in case of motor-blower failure, as previously mentioned, is possible.

If tests, for some reason not presently anticipated, show that the accumulation of ice in the dehumidifier affects the performance adversely over the duration considered, a modification of the air conditioning unit according to Figure 6-3 may be considered. This arrangement is characterized by a dehumidifying section that can be replaced. The section consists of aluminum sheets held together by Mylar film which opens up like a fan when placed in the circuit. After an accumulation of ice, it is removed and placed in a plastic bag. After the ice has melted, the device may be folded, thus squeezing out the water. Wedges of ice may also be recovered directly if desired.

6.3.2 Cryogenic Containers

Data for the prototype design was obtained from the subsystem study on cryogenic containers (Appendix VIII). The Dewar constructed tanks used differ little from standard constructed tanks. For the volume of either gas required in this design, minimum thickness limitations for fabrication rather than stress considerations controlled tank thickness. The containers used external heaters to maintain the fluids above the critical point and expel them as a single phase. It is believed that such a system represents a simplification over the use of pumps and also has improved reliability. Considering the weight of the pump versus the weight penalty of heaters and heater power required for this particular system, the advantage was slightly in favor of the heaters. The amount of gas remaining in the tanks was assumed to be the same in both cases.

In spite of the reference made to heating the cryogenics, the expelled gases are still far below ambient which permits them to be used for dehumidification and cooling. The amount of heat required to expel the gases represents a relatively small part of the electrical energy potential of these gases. The actual heat required in the form of electrical energy varies, depending on the amount of gas in the tank at any time, but averages 3 watts for the hydrogen tank and 8 watts for the oxygen tank. Since the flow rates involved are for a one-kilowatt power rating for the fuel cell, it is evident that the electrical-heater power represents 1% of the output of the system. The heater requirements are augmented by the natural heat leakage from ambient which for the hydrogen tank supplies almost all of the heat necessary for the expulsion over most of the mission's duration. The heating method for expulsion also provides a convenient and simple means for monitoring the amount of fluid remaining in the tanks at any time since the temperature gradually increases. Thus by measuring the temperature, pressure, and container volume, the amount of gas remaining may be readily computed (see Appendix VIII).

Fluids are supplied to the special pressure-regulating valve at 800 psi. As the gases are used up in the cell, the pressure gradually drops. This information is transmitted back to the pressure sensors via the fluids. The sensors turn the heaters on, thus expelling more fluid into the system.

Those familiar with cryogenic containers will note that the system weights computed and presented in Appendix VIII represent a considerable improvement over the present state of the art. While some of the gain may be ascribed to the use of titanium rather than stainless for the inner shell, the most probable explanation is the conservatism of present design standards. The system weights recommended above are believed consistent with other risks involved in the proposed application.

6.3.3 Fuel Cell System

Estimates of weights and performances of hydroxy fuel cells have been made largely on the basis of estimates by Patterson-Moos Division of the Universal Winding Company as reported in WADD Technical Report 57-605 dated September 1957. It will be recalled from Section 5.0 that the cell weight and efficiency depend on the loading per unit area of cell. This loading may be expressed in terms of the current density, amps per square foot (ASF). The higher loading results in lower cell weights but higher fuel consumption. In the present study, fuel cell system weights were optimized in terms of fuel cell weights and cryogenic storage for the H_2-O_2. These results are summarized in Section 5.0 and Appendix IX. For the prototype design, the results were applied to a one-kilowatt fuel cell system for a three-day mission. Figure 6-4 shows as a function of current density the fuel cell weight which includes 30 pounds for controls (curve C), the cryogenic hydrogen storage system weight which includes fuel, tank, and 8 pounds for valves and miscellaneous hardware (curve A), a similar plot for the cryogenic oxygen storage system (curve B), and

WEIGHT VS CURRENT DENSITY FOR 1-KW, 3-DAY MISSION

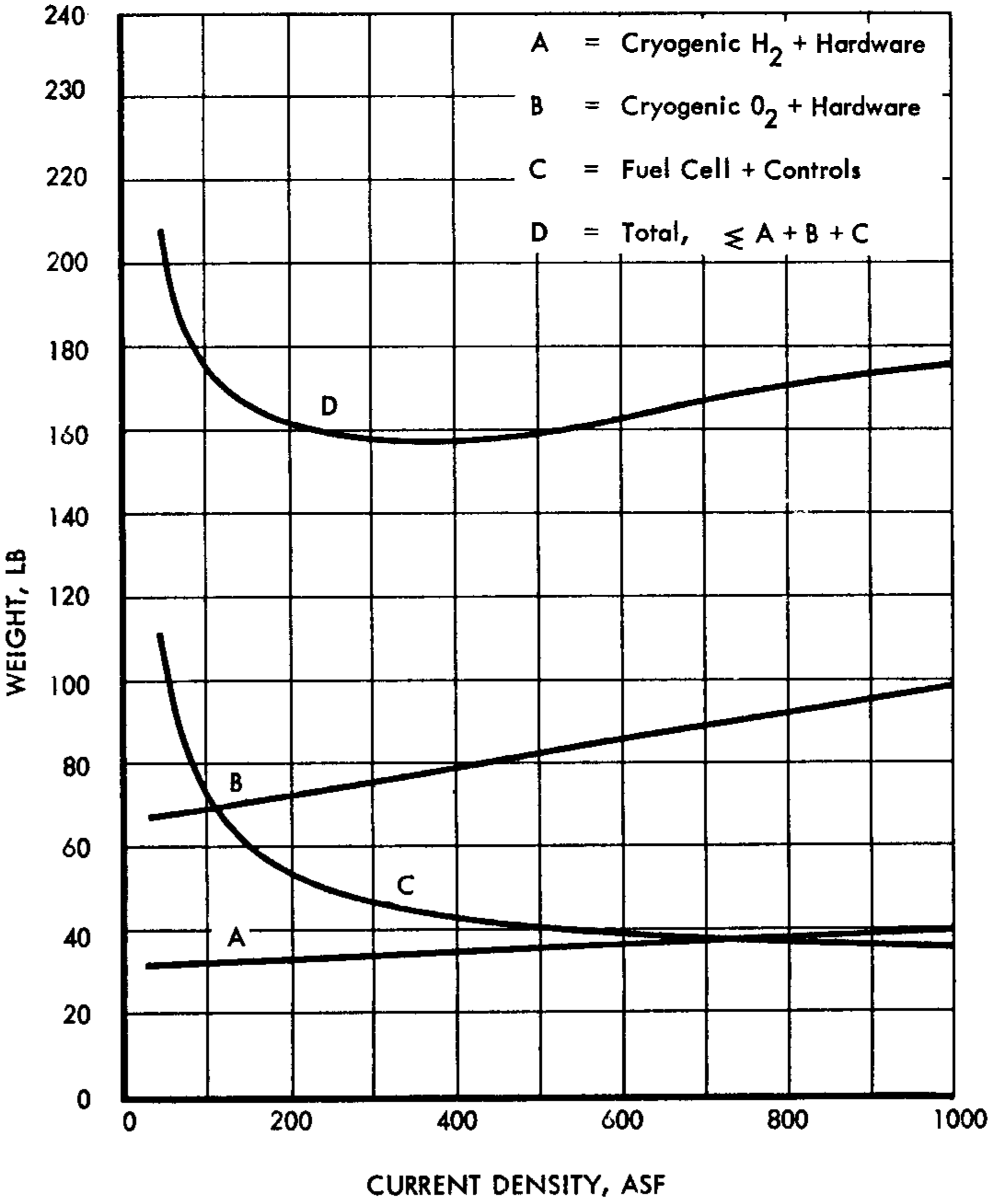


FIGURE 6-4

finally the sum of all of these or the weight of the power system. A minimum of about 160 pounds will be noted for the total weight and the value is approximately constant over a large range of current densities. Since present fuel cell weights appear to be on the heavy side, one can allow 52 pounds for the fuel cell system (22 pounds for the cell and 30 pounds for the hardware) without affecting the total power system weight significantly.

Present fuel cell technology has been reduced primarily to materials problems rather than design. Thus no attempt has been made in this prototype study to design a cell. Various design aspects, some of which are reproduced in Figure 6-5, have been reproduced from WADD TR 57-605 to give an idea of structural concepts. Pressure control, heat and water removal from the cell and voltage control are treated at greater length in the following sections.

Pressure Regulator

The differential regulator is a combination valve pneumatically operated to provide proper regulation for the three gases (hydrogen, oxygen, and nitrogen) which are supplied to the fuel cell. The tilt valves between the inlet and outlet ports of both hydrogen and oxygen have been fully developed and are supplied to the Air Force in the form of oxygen aircraft mask valves. They are housed in the right and left subassembly, Figure 6-6. These tilt valves provide the pressure reduction and regulation from inlet port to the diaphragm chamber.

The valve operates as follows. With less than 600 psi, the force transmitted to the bellows by piston P exceeds that of the N_2. This is transmitted by the lever to the needle valve V_1 and since it overpowers S_3 the needle valve remains closed. Nitrogen continues to flow into N and the pressure builds up until the force on the bellows exceeds S_1. At this point the force on the levers is reduced and S_3 opens up the needle valve, allowing nitrogen to escape to maintain the pressure constant. The pressure in N is communicated to the H and O chambers by the N_2 gas via the diaphragms. Considering the H side, the tilt valve T_H is normally in the closed position since S_4 normally overpowers S_5. When the pressure in N reaches about 600 psi, the additional force on the diaphragm is sufficient to push it to the right tilting valve T_H. Thus the nitrogen pressure has a biasing effect on both the regulated oxygen and nitrogen so that not only do the nitrogen and oxygen have equal regulated pressures but also the difference between the nitrogen and oxygen as well as nitrogen and hydrogen is kept at a constant 2 ± 0.2 psi. Another function of this nitrogen is to act as pilot pressure so that when the nitrogen is turned off, the combination valve acts as a shutoff valve. The spring plus the nitrogen acts on both diaphragms to open the respective regulator tilt valves. When the nitrogen gas is exhausted both tilt valves are forced to the closed positions by the tilt valve spring. This differential regulator, schematically shown in Figure 6-6, consists of standard developed items even though this is a modified configuration.

FUEL CELL LAYOUT

GENERATOR HOUSING

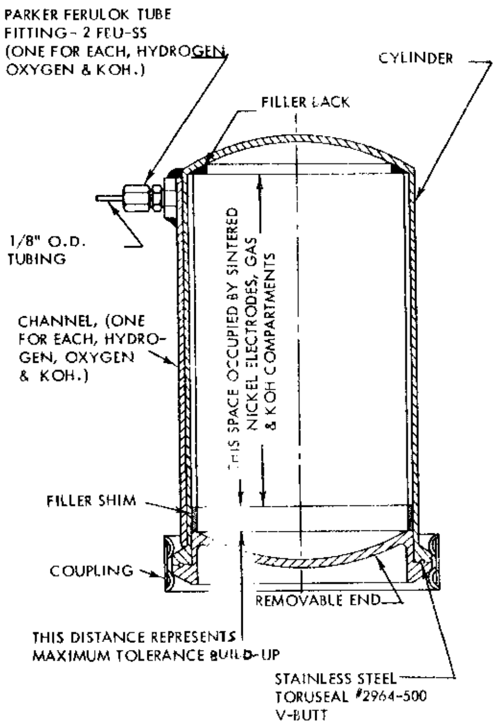


FIGURE 6-5A

ARRANGEMENT OF PORT OF ENTRY FOR KOH, HYDROGEN AND OXYGEN, WHICH LINE UP WITH APPROPRIATE FEED THROUGH CHANNELS IN CYLINDER

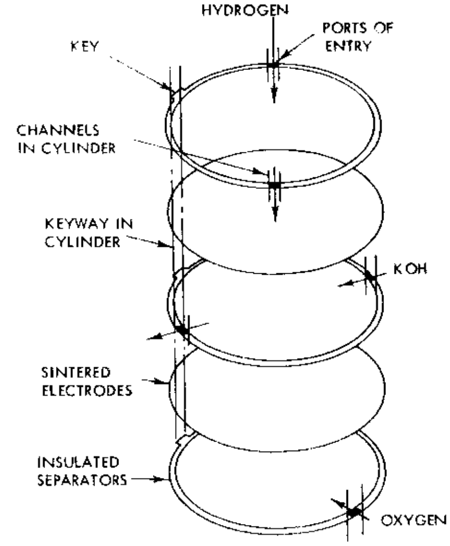


FIGURE 6-5B

ELECTRODE ASSEMBLY

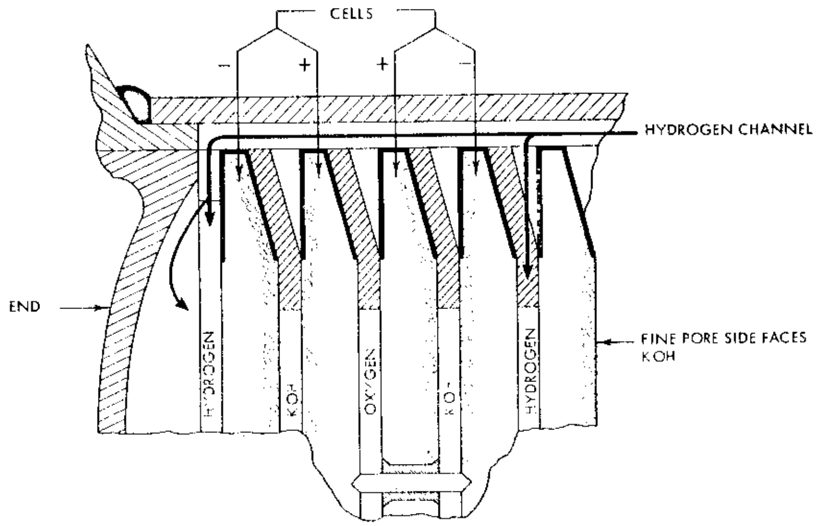


FIGURE 6-5C

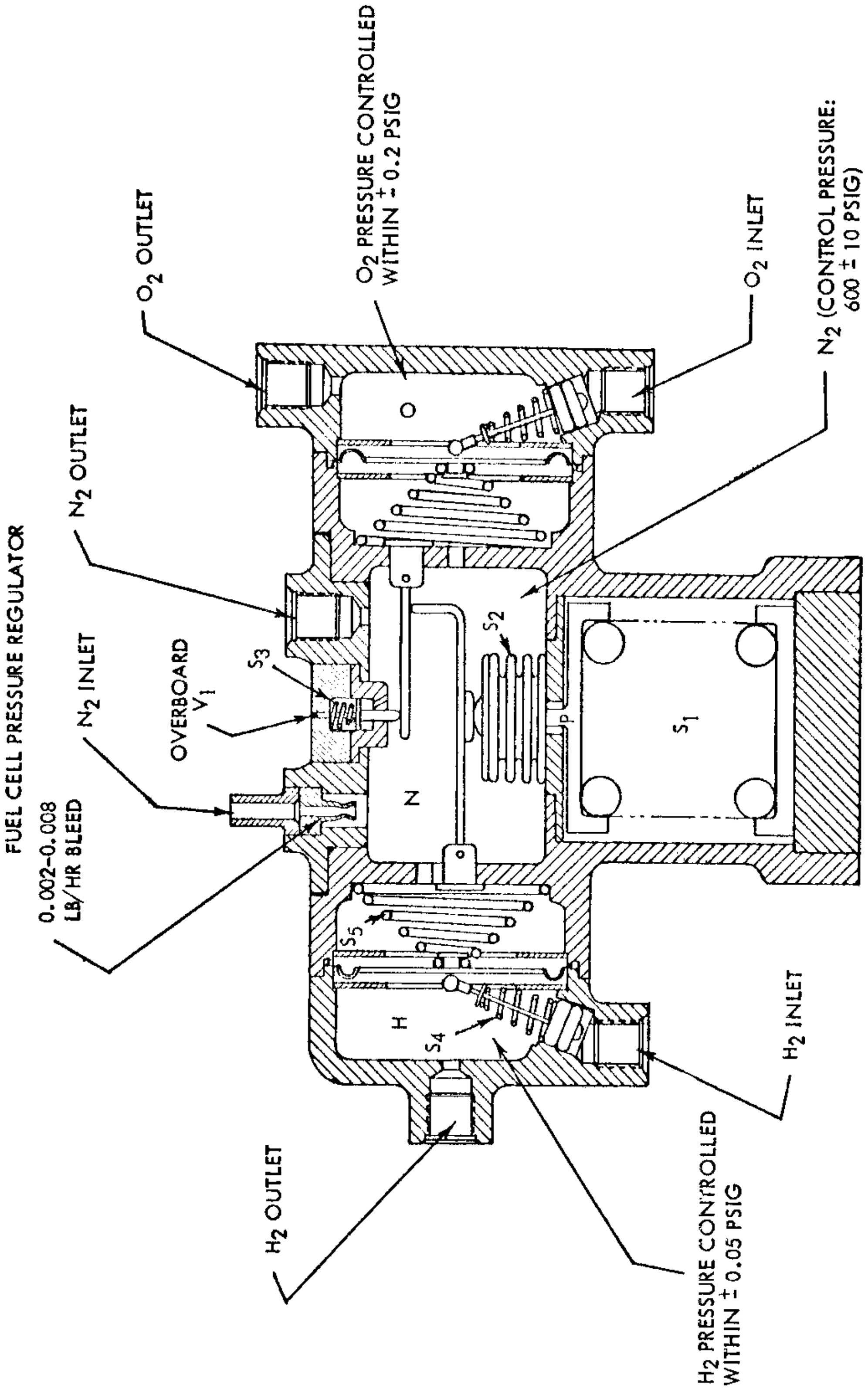

FUEL CELL PRESSURE REGULATOR
0.002-0.008 LB/HR BLEED
N_2 INLET
OVERBOARD V_1
S_3
N_2 OUTLET
O_2 OUTLET
O_2 PRESSURE CONTROLLED WITHIN ± 0.2 PSIG
O_2 INLET
N_2 (CONTROL PRESSURE: 600 ± 10 PSIG)
O
N
S_2
S_1
P
H
S_4
S_5
H_2 OUTLET
H_2 PRESSURE CONTROLLED WITHIN ± 0.05 PSIG
H_2 INLET

FIGURE 6-6

Hydrogen-Water Separator

Essentially the hydrogen-water separator is a combination centrifugal pump and compressor, Figure 6-7. The inlet port admits the fluid which consists of hydrogen gas and water. The rotating member creates centrifugal force, causing the water to accumulate on the outer surfaces of the water cavity. The separation is caused by the difference in density between water and the hydrogen. The water valve is provided to build a water dam on the circumferential surface of the water cavity so that hydrogen will not blow out the water port. The second stage of the rotating assembly is the centrifugal compressor which is required to recirculate the gas in the hydrogen loop. The pressure rise of the compressor is equal to the line drop through the loop. The hydrogen gas is collected in a volute and passes out the outlet port. Two face seals prevent the hydrogen from leaking into the separator drive or into the capsule. Any leakage which might occur is vented overboard.

This type of hardware is well within the state of the art and similar to many models of TRW water and fuel pumps now in airborne equipment. The gas compressor is also similar to many items developed by TRW. A power consumption of 30 watts has been estimated for the unit. This is a mere guess but probably as valid as guessing the pressure drop through the system. Any estimate of pressure drop through the system would have been sheer speculation in view of two-phase flow, channels, ports, etc., that the fluids must flow through. Estimation of power consumption must be deferred pending actual testing of the systems.

Nitrogen Tank

The nitrogen is supplied at a pressure of 7000 psi and is bled at a rate of 0.002 to 0.008 pound/hour in the pressure regulating valve. This is about 0.6 pound for the mission. The tank plus nitrogen weighs 3 pounds and has been included as part of the fuel cell control weight.

Cooler-Condenser

A total of 3400 Btu/hour must be removed from the fuel cell; this can be accomplished partially by the use of a condenser whose primary purpose is to abstract the water being generated in the cell. Calculations show that 1100 Btu/hour will be removed from the unit. At a radiating temperature of 400°to 460°F, the load can be handled with one square foot of radiating surface outside the capsule. The remaining load of 2300 Btu/hour may be removed by circulation of the electrolyte through a similar space radiator that would require about 2.3 square feet of surface. The total surface required for the cooler-condenser is approximately 3 square feet; it will weigh 1.5 pounds. This weight is included as part of the fuel cell control. The calculated power requirements of the circulating pump are negligible.

HYDROGEN-WATER SEPARATOR AND COMPRESSOR DESIGN

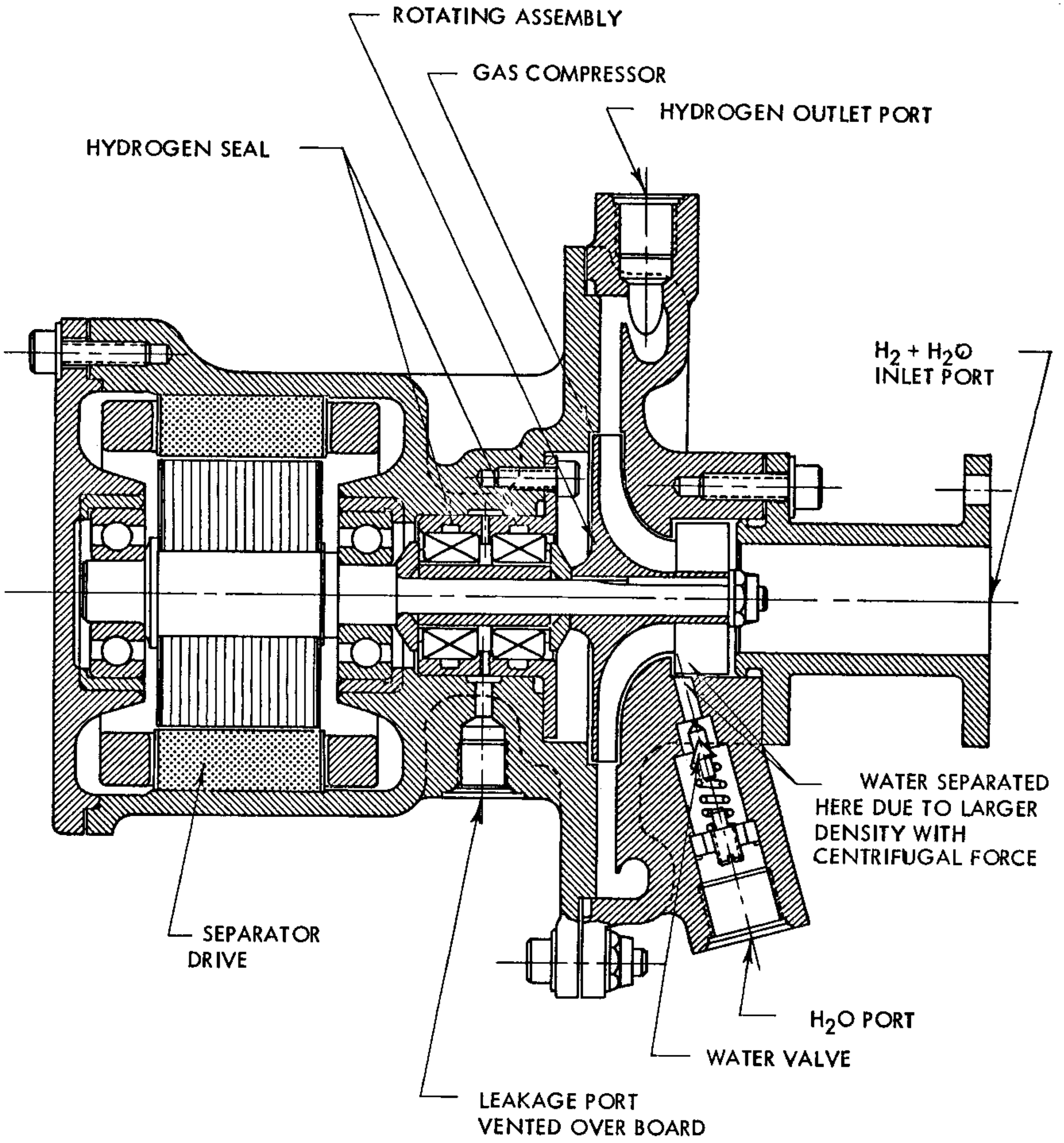


FIGURE 6-7

Voltage Regulation of Fuel Cell Output

A voltage regulation between 26 and 29 volts, the same as used in the WADD Technical Report 57-605, was assumed. This generator regulation is accomplished by switching more or less cells in series with generator terminals as the load varies. A nomograph, Figure 6-8, has been prepared to show the relationship between load, voltage, current density, cell voltage, and finally, generator voltage.

The lower left quadrant shows parametrically the relationship between generator load, generator current and generator voltage. Since the cells are in series to form the generator, the generator current equals the cell current. The y axis is expressed as the cell current. The lower right hand quadrant shows the relationship between current density, cell area and cell current. This nomograph can be used as a tool to modify the fuel cell design, if need be. The cell area was taken at 19.6 square inches as called out in the WADD report.

The upper right hand quadrant shows the relationship between cell voltage and current density (obtained from WADD TR 57-605). The upper left hand quadrant shows the multiple of cells required to keep the generator voltage within the regulated voltage tolerance. For low loads 30 cells are required while for high load 33 cells are required for our design. In the middle range there is an overlap (either 30 or 33 cells will suffice) to handle the hysteresis of our sensing equipment. The tolerance can be reduced by adding smaller increments of cells if required at the cost of a slight additional weight and complexity.

Figure 6-9 shows the electrical diagram with additional cells, in phantom. The voltage regulator has two voltage sensors; the first is a Zener diode and gives current flow above 29 volts while the second Zener diode gives current above 26 volts. These signals are amplified in Figure 6-10. The approximate signal will trigger the flip-flop, energizing or de-energizing the preamplifier relay. This in turn energizes or de-energizes 1 CR which adds or subtracts the 3 cell increment to the 30 cells in a series configuration. This component will take up a space 4 inches x 1 1/4 inches x 3/4 inch.

6.4 GAS ANALYZERS

Carbon dioxide, oxygen, hydrogen and relative humidity analyzers were incorporated in the design and used for atmosphere control.

6.4.1 Carbon Dioxide Partial Pressure Analyzer

Equipment is provided to sense the concentration of carbon dioxide gas in the capsule atmosphere, provide visual and electrical indications of concentration, and activate an indication circuit at a preset maximum level of concentration. The device consists of a carbon dioxide sensor, an electronic signal amplifier and a meter for visual readout.

NOMOGRAPH FOR VOLTAGE REGULATION

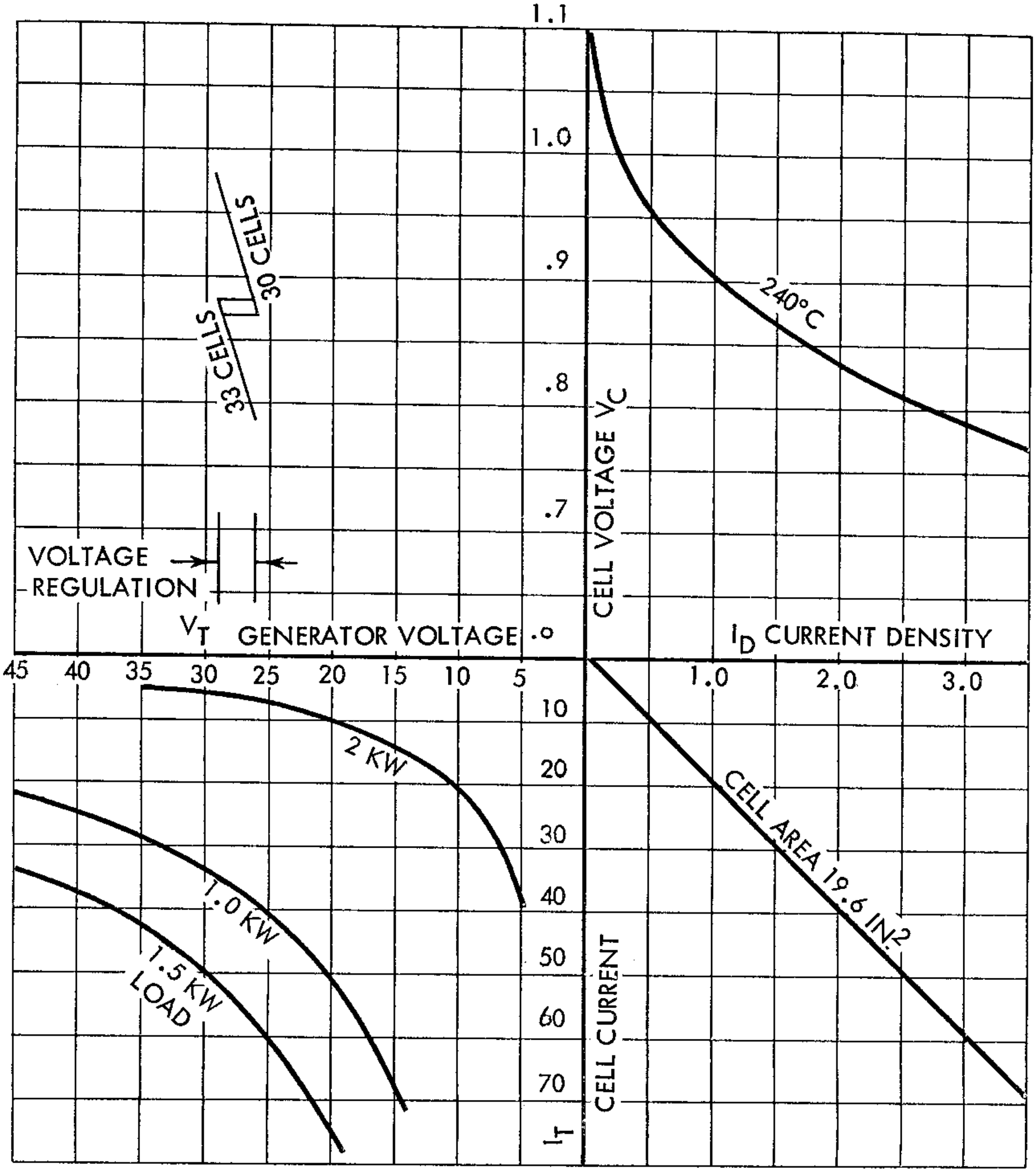


FIGURE 6-8

PRELIMINARY ELECTRICAL WIRING DIAGRAM

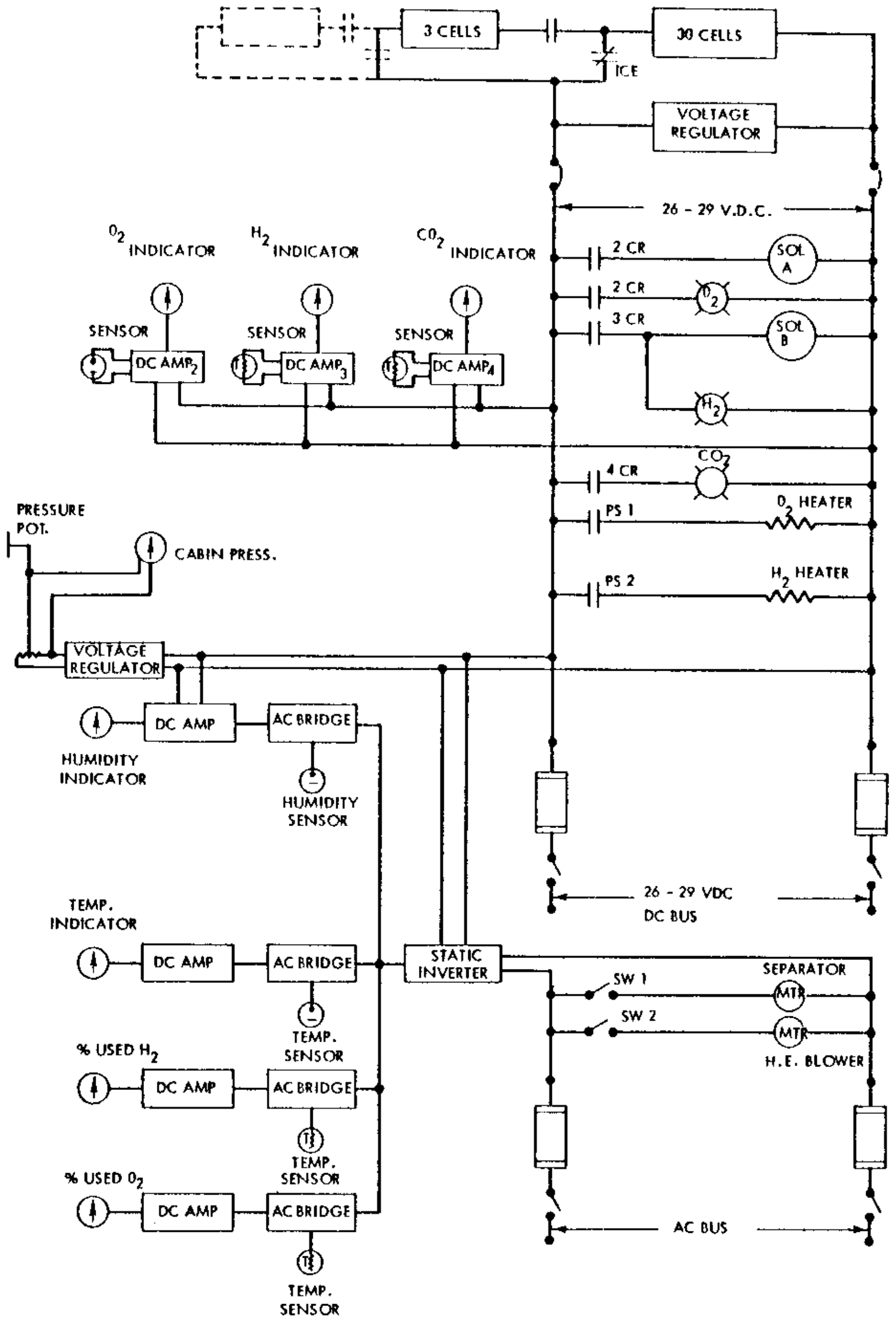


FIGURE 6-9

VOLTAGE REGULATION PACKAGE

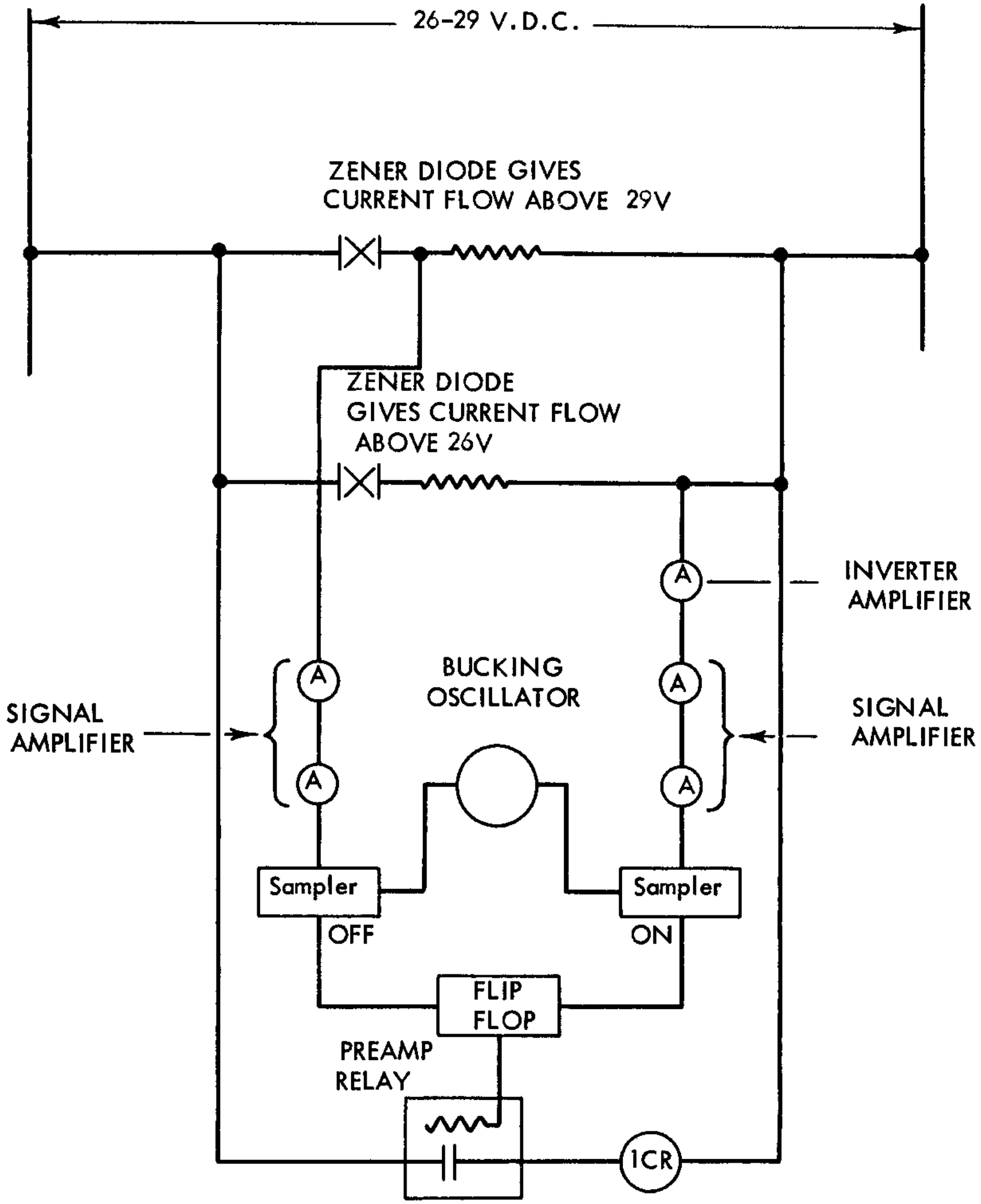


FIGURE 6-10

The CO_2 sensor is based on the principle of the change in pH of an electrolyte caused by the formation of carbonic acid when exposed to an atmosphere containing CO_2. This device is similar to the Beckman O_2 sensor but uses a quinhydrone solution for the electrolyte. Although the sensor is not completely quantitative, its stability is sufficient for use as an alarm point anywhere within the range of 1 to 50 millimeters pCO_2. Since the sensor reads directly in terms of partial pressure of CO_2, the device is independent of absolute pressure. The electrode does exhibit a fairly large temperature coefficient, however, which requires that the sensor be either temperature regulated or that the sample gas be passed through a temperature-regulated heat exchanger to provide stability over wide temperature ranges. Temperature compensation will be provided by thermistors in the amplifier circuitry.

In normal operation, the sensor signals are amplified for visual and telemeter readouts. In the event that the carbon dioxide rises to the preset levels, the maximum limiting circuit provides a signal to a signal light on the control panel. The astronaut will take suitable steps to change the CO_2 absorption cartridge.

This CO_2 sensor has been fully developed by the Beckman Instrument Company and is now being used on Project Mercury. The stability of this unit is affected in temperature ranges of $65^{\circ}$to 75°F; therefore, the temperature should be controlled and the unit kept as cool as possible to provide the greatest reproducibility and accuracy. The sensor in this design is located in the environmental chamber immediately forward of the dehumidification heat exchange. This unit performs best in a wet atmosphere and will fail at zero humidity because of water absorption from the electrolyte. The physical dimensions of the sensor (Figure 6-11) are given in Table 6-1.

6.4.2 Oxygen Partial Pressure Analyzer

Equipment to sense the partial pressure of oxygen in the capsule atmosphere will consist of a sensing element, an electronic signal amplifier, and a visual readout device. It will activate the solenoid valve at a preset minimum. The signal amplifier is the one referred to in discussion of the CO_2 analyzer. The principle of operation of the device is based on electrochemical reduction of oxygen on an inert gold electrode. As a result of this reduction process, a current is produced which is directly proportional to the oxygen partial pressure in the gas surrounding the transducer.

The oxygen partial pressure sensing element has an electrochemical sensor of the polarographic type which consists of a gold electrode and a cadmium reference electrode. The gold electrode is provided with a diffusion barrier consisting of a layer of silicon grease, plastic membrane, and a layer of electrolyte solution. A reference electrode of cadmium is used, which permits a spontaneous reduction of oxygen without the application of a polarizing voltage because of its potential. In certain applications, however, a small polarizing voltage is applied. The flow of current is so small that only micromolar quantities of oxygen are reduced within any reasonable time of operation.

CO$_2$ SENSOR (BECKMAN)

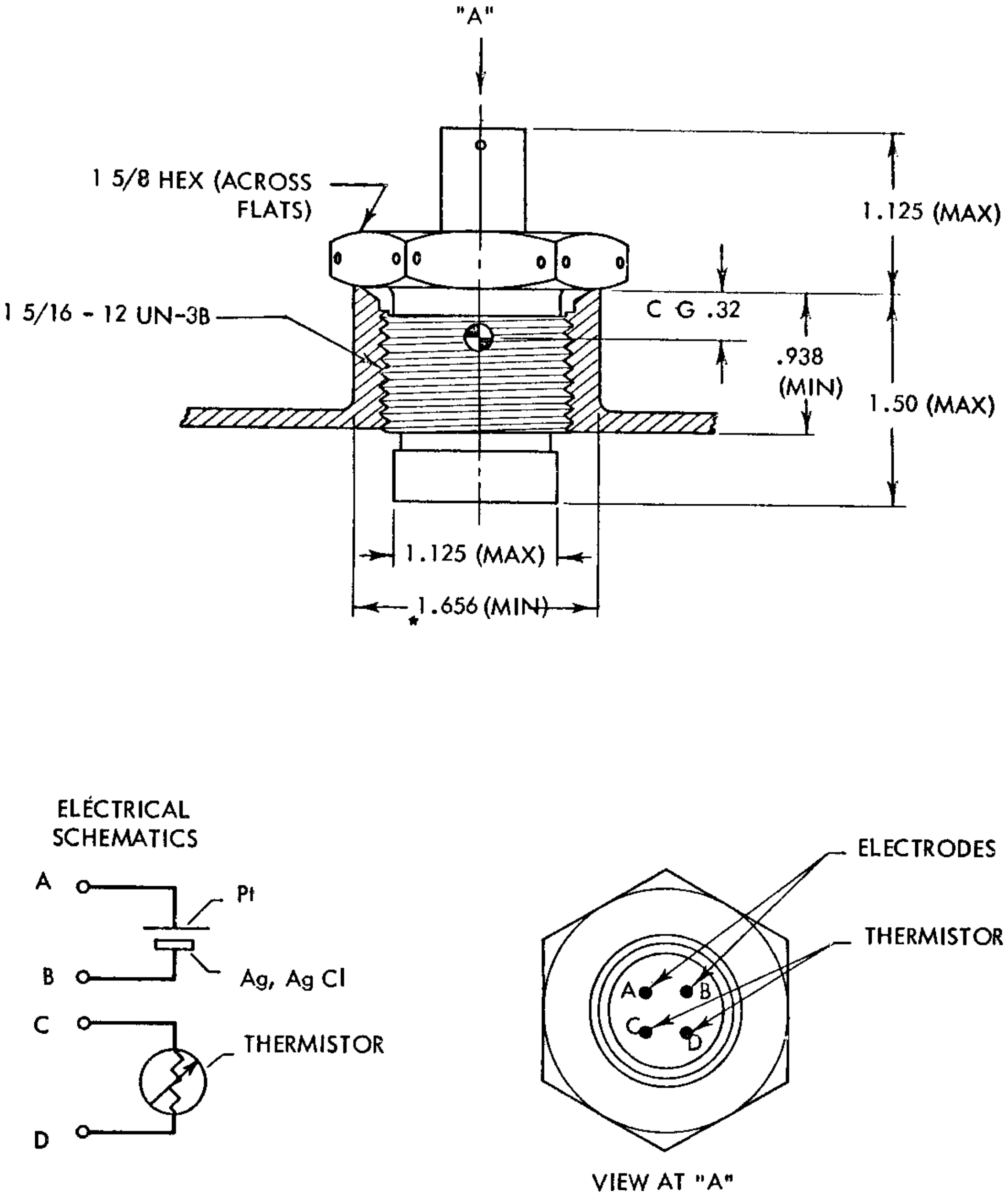


FIGURE 6-11

TABLE 13

PARAMETRIC DATA FOR PARTIAL PRESSURE ANALYZERS

CO_2 PARTIAL PRESSURE SENSOR

Response Time	3 minutes minimum time constant
TemperatureCoefficient	0.4 millivolts/°C
Weight	4 ounces maximum
Power Required	0

	PARTIAL PRESSURE SENSOR H_2	PARTIAL PRESSURE SENSOR O_2
Size	2 inches diameter, 3 inches long	1.5 cubic inches
Weight	3 pounds	1.6 ounces
Power Input	5 watts	0
Response Time	2 seconds, full scale	< 1 minute

CO_2, O_2, H_2 ANALYZER AMPLIFIERS

Power Consumption	0.17 watts, 24 volts, DC
Gain	40 to 80, adjustable
Input	0 to 50 millivolts
Linearity	1% full scale
Output Voltage	0 to ± 5 volts DC
Size	4.43π x 2.5 inches x 1-3/8 inches
Weight	9 ounces

RELATIVE HUMIDITY ANALYZER

Weight	0.8 pound
Power Requirements:	
DC	0.2 watt, 24 volts
AC	0.3 watt, 115 volts, 400 cycles
Dial Calibration	20 to 100% RH
Typical Accuracy	± 5% over 40 to 60% RH, 65 to 75°F range
Temperature Limits	65 to 200°F

A sensor or transducer similar to that intended for the Mercury capsule is made by J. Ryan Neville (Figure 6-12). The Neville GP-1 model transducer is contained within a total volume of about 1.5 cubic inches. The weight without cable is 1.6 ounces. This transducer is designed for a range of 0 to about 800 millimeters mercury oxygen partial pressure or any part of this total. Its output is approximately 0.25 millivolt or 0.025 microamp per millimeter mercury oxygen pressure at 25°C. The TRW amplifier is suitable for use with the GP-1 and will give full scale deflection with one millivolt DC or lower.

Experimental investigation indicates that the main source of error and instability is related to the large temperature coefficient of the device (approximately 5%/°C at 25°C). Compensation may be obtained with a thermistor element. Proper choice of thermistor can generally keep the output within 5% of the mean over a temperature range of 0° to 50°C. The transducer is highly specific to oxygen when used in a gas mixture suitable for ordinary breathing purposes. Nitrogen, helium, carbon monoxide, carbon dioxide, and water vapor are known from experience to be without direct effect. Most gases and vapors have little influence according to information on the oxidation-reduction potentials.

6.4.3 Relative Humidity Analyzer

A device is provided to sense the level of relative humidity in the capsule and provide visual and electrical indications. It consists of a relative humidity sensor, an electronic signal amplifier, and a meter for visual readout. The principle of operation is the change in insulation resistance of a thin film, with accompanying changes in relative humidity. The unit consists of a ceramic gold grid electrode made humidity-sensitive by means of a film of polyvinyl alcohol impregnated with lithium chloride. Sensor resistance is a function of the partial pressure of water in the surrounding atmosphere and is not affected by barometric pressure or gas composition. Sensor resistance is compared to a temperature-compensated reference resistance in a 400-cycle AC Wheatstone Bridge Circuit. The output is amplified to the 0 to 5 volts DC telemeter levels and fed to a 250-degree scale millimeter movement to provide a visual display.

This sensor is a modification of the unit manufactured by Minneapolis Honeywell Co. for Project Mercury. The only difference is the addition of an amplifier to provide signals in the 0 to 5 volts DC range. It consists of a MS-33598 instrument case measuring 2.0 inches diameter across the bezel and 4.75 inches long. The ventilated rear case section contains the humidity sensor and temperature compensating network. The transistor amplifier and meter movement are contained in the hermetically sealed front section. Physical data on this unit are presented in Table 6-1.

6.4.4 Hydrogen Partial Pressure Analyzer

A device is provided to sense the concentration of hydrogen gas in the capsule atmosphere, provide visual and electrical indications of concentration, and activate the emergency control system at a preset maximum level of concentration.

TRANSDUCER, OXYGEN PARTIAL PRESSURE

MOUNTING DIMENSIONS

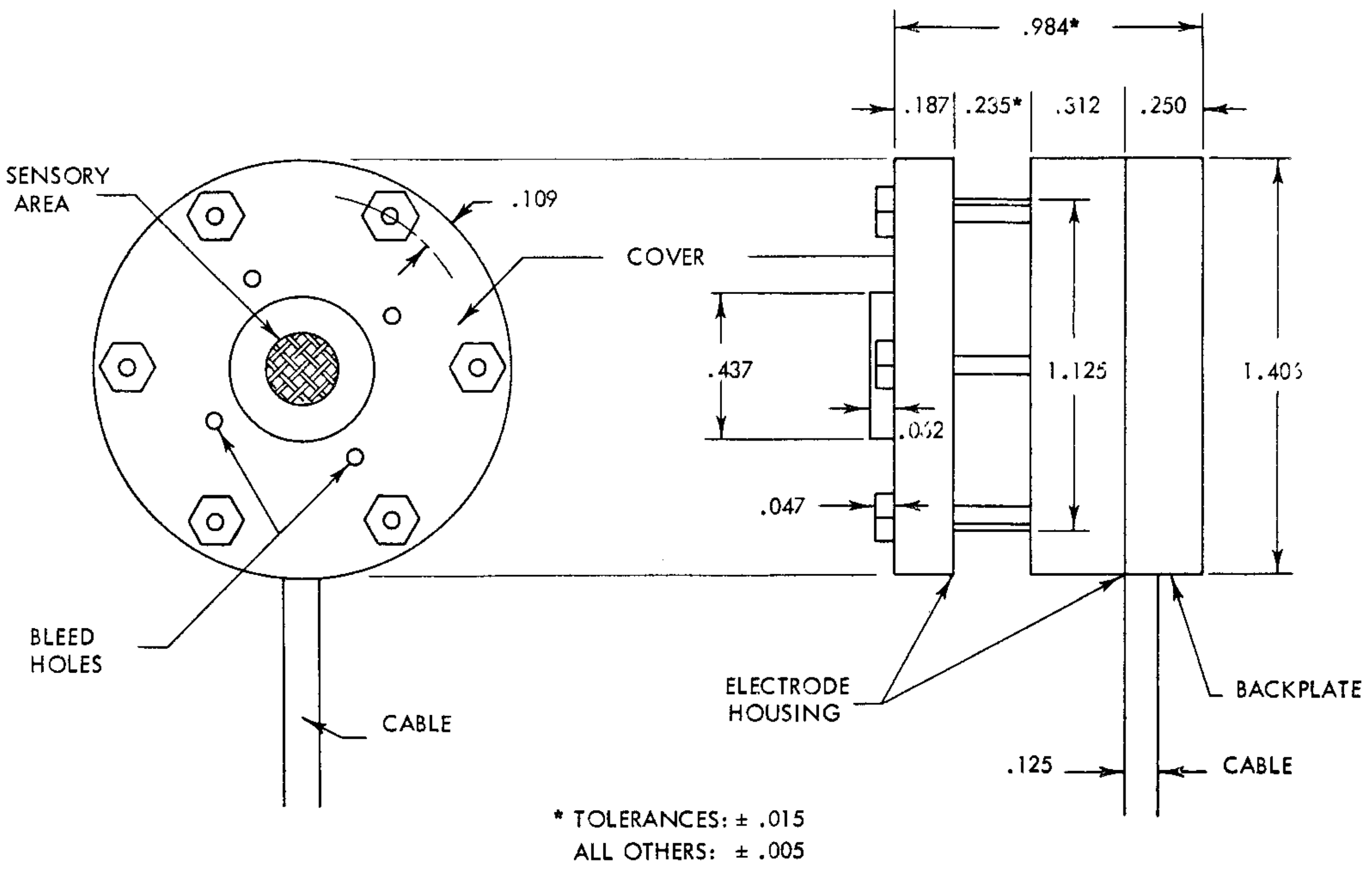


FIGURE 6-12

There are a number of devices that can satisfactorily measure 0 to 5% hydrogen in an oxygen atmosphere, the simplest of which is a thermal conductivity cell consisting of a bridge containing filaments or thermistors. Two legs of the bridge are exposed to the sample atmosphere and the other two legs are exposed to a reference gas which contains a known concentration of H_2. The principle of operation is the measurement of the change in resistance of the arms of the bridge due to heat losses from the filament which are a function of the thermal conductivity of the gas to which the filaments are exposed. Since the thermal conductivity measurement is a function of temperature, it is generally necessary to support the filament bridge within a large mass to provide good stability. Thermal conductivity of hydrogen gas is quite different from oxygen and CO_2, and therefore a large differential signal should be obtained in the presence of small amounts of hydrogen. Operation of the bridge requires a stable DC power supply and the output of the bridge must be amplified by a low-level amplifier.

An electronic amplifier is provided to furnish a stable DC power supply to the sensor bridge circuit and amplify the output signal of the sensor to the 0 to 5 volts DC levels required for input to telemetering transmitters. A maximum limiting circuit is incorporated in this unit to provide a signal at a preset maximum level of concentration. A calibrated micro-ohm meter is provided on the control panel to provide a visual readout. This unit will be shunted across the output signal to the telemeter radio. The control panel will also contain a signal lamp in the maximum limiting circuit to furnish a visual signal of maximum concentration. In normal operation, the sensor signals are amplified for visual and telemeter readouts. In the event that the hydrogen concentration rises to the preset levels, the maximum limiting circuit provides a signal to turn on the motor-blower, sending the air through the catalytic bed.

To our knowledge, no unit has been developed to date for the measurement of hydrogen, but several firms have expressed interest in developing a unit of this nature. It appears necessary to regulate the temperature of the thermal conductivity cell to approximately 1 degree to provide sufficient stability for this measurement. The gas sampling will rely on diffusion through the gas head as opposed to providing a sample pump. This is feasible because of the free movement of atmosphere provided in a gravity-free environment. It reduces space and weight requirements and the potential sparking hazard of a DC motor. Tungsten carbide flashback arresters are provided on the sensor. The amplifier consists of a modified version of the transistorized unit built by TRW for O_2 and CO_2 measurements in Project Mercury. Physical characteristics of both the sensor and amplifier are given in Table 6-1.

A preliminary study was made of alternate methods of sensing the partial pressure of hydrogen in the capsule atmosphere and the following alternates were considered:

1. Platinum wire combustibility
2. Thermal conductivity
3. Sonic velocity
4. Nuclear magnetic resonance
5. Mass spectrometers

The operation of a sonic velocity meter appears somewhat doubtful in the low concentration regions desired. The nuclear magnetic resonance and mass spectrometer principles in laboratory-type instruments do not seem to lend themselves to the rugged service and miniaturization required for this application. The combustibility meter presents an explosion hazard. Thus a unit using the principle of thermal conductivity appears to have the most promise.

6.5 SUMMARY

Major subsystems studies required in the prototype design have been relegated to the Appendices. These include cryogenic storage weights (Appendix VIII), hydroxy fuel cell system analysis (Appendix IX), and dehumidification and cooling (Appendix X).

The process design for the propellant-atmosphere system to supply 1 kilowatt of electric power and accommodate one man for a period of three days is summarized in Figure 6-1. The implied assumption in the design was that no additional cooling over and above that supplied by the cryogenic system and passive cooling of the capsule would be required. Whether or not this is realistic cannot be ascertained until all factors related to the mission and capsule structure have been integrated in a vehicle system design. The design is by no means complete but does illustrate the general concepts that would be involved in a system of this nature, the analysis, and feasible layout of the air conditioning unit as well as the entire equipment (Figure 6-13). Table 6-2 summarizes the system characteristics of the prototype design.

TABLE 6-2

SYSTEM CHARACTERISTICS OF PROTOTYPE DESIGN

WEIGHT SUMMARY

Air Conditioning Unit

LiOH	9 Pounds
Activated Carbon	1.5
Filter	0.25
Dehumidifier	2.0
Motor-Blower	4.0
O_2 Supply	6.0
O_2 Analyzer	2.0
O_2 Valves, Control	2.0
CO_2 Analyzer	2.0
Humidity Analyzer	2.0
H_2 Analyzer	3.0
H_2 Oxidizer Unit	4.0
Duct and Supports	4.0
Total Weight	42.0 Pounds

Power Unit

H_2 (8 pounds) Cryogenic Storage	36 Pounds
O_2 (62 pounds) Cryogenic Storage	82
Fuel Cell System	41
Total Weight	159 Pounds
Total System Weight	201 Pounds

ELECTRICAL POWER REQUIREMENTS

Motor-Blower for Air Conditioner	23 Watts
Separator-Blower for Fuel Cell	30
Motor-Blower (H_2 Oxidizer)	0 to 10
Circulating Pump	10
Gas Analyzers	5
Total Power	68 to 78 Watts

MAJOR SPACE REQUIREMENTS

Cryogenic H Tank, 20 inches diameter	2.42 cubic feet
Cryogenic O Tank, 16 inches diameter	1.24
Air Conditioning Unit, 7 x 28 inches	0.62
(Second LiOH Canister, 7 x 10 inches)	0.22
Fuel Cell, 8 x 12 inches	0.35
Total:Major Units	4.85 cubic feet
Auxiliary Hardware and Controls	1.5
TOTAL SPACE REQUIREMENTS	6.35 cubic feet
MAXIMUM OVERALL DIMENSIONS	2 x 3 x 2 feet

LAYOUT OF PROPELLANT-ATMOSPHERE SYSTEM

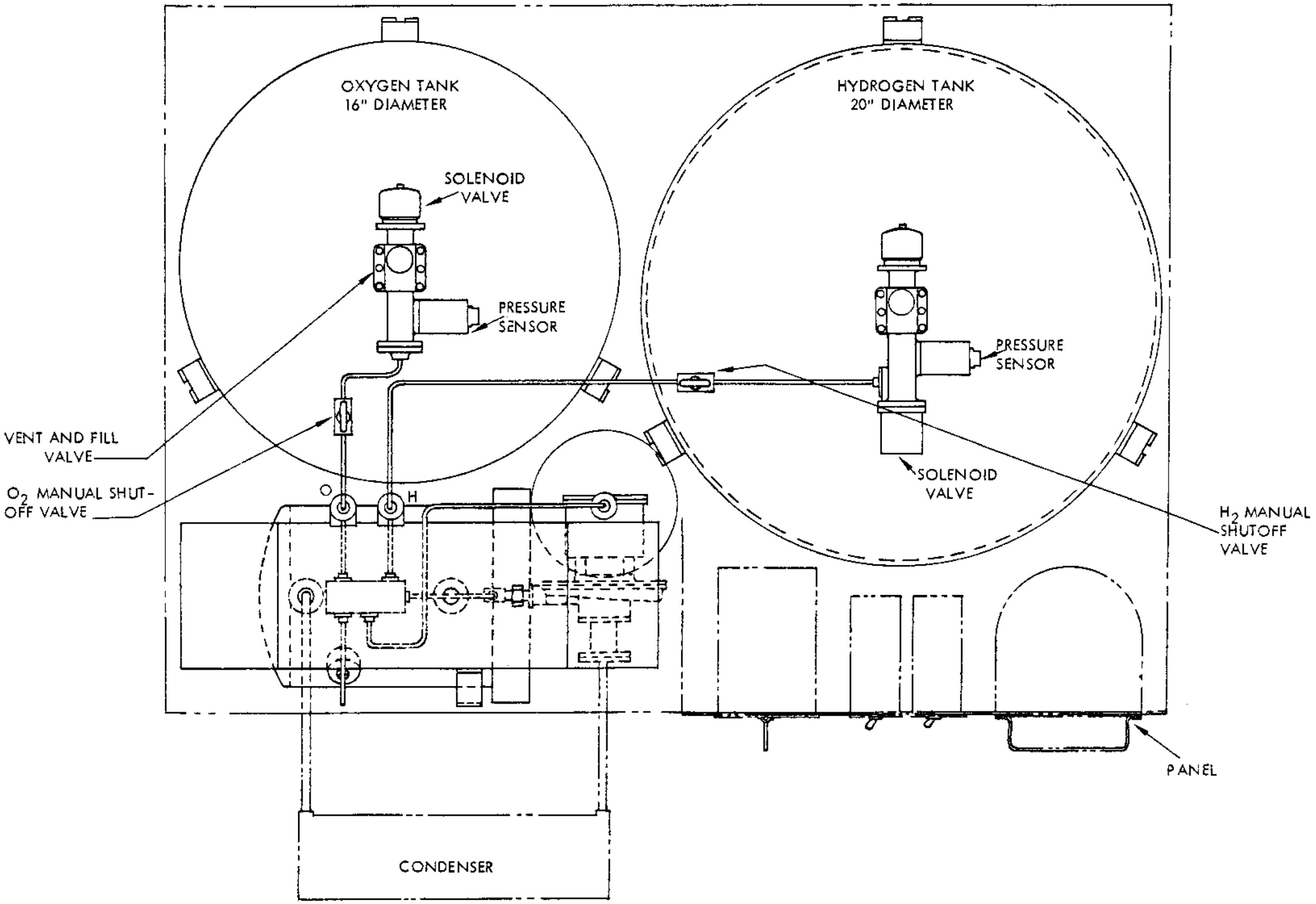


FIGURE 6-13A

PROPELLANT-ATMOSPHERE SYSTEM (SIDE VIEW)

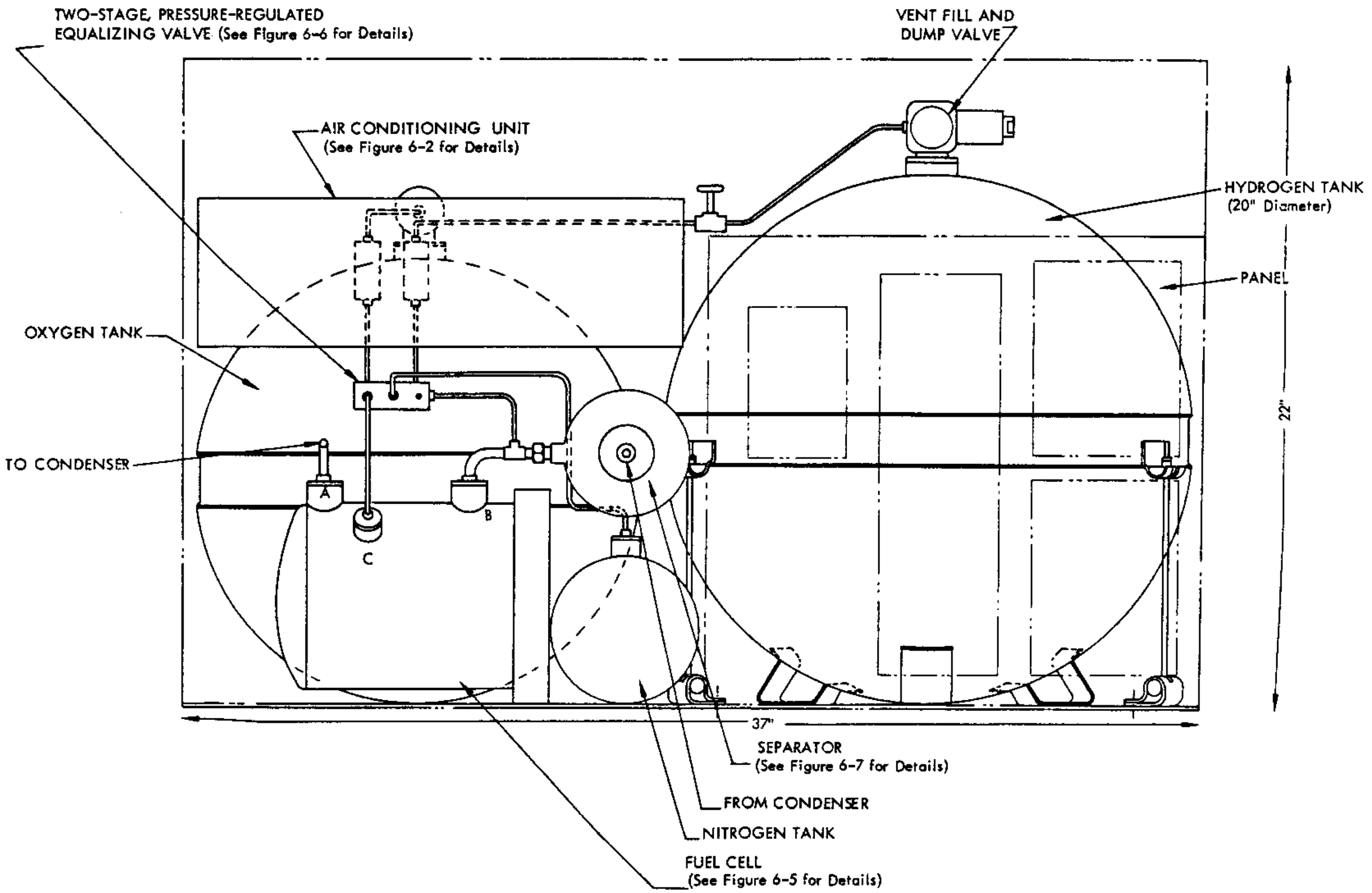


FIGURE 6-13B

PROPELLANT-ATMOSPHERE SYSTEM (END VIEW)

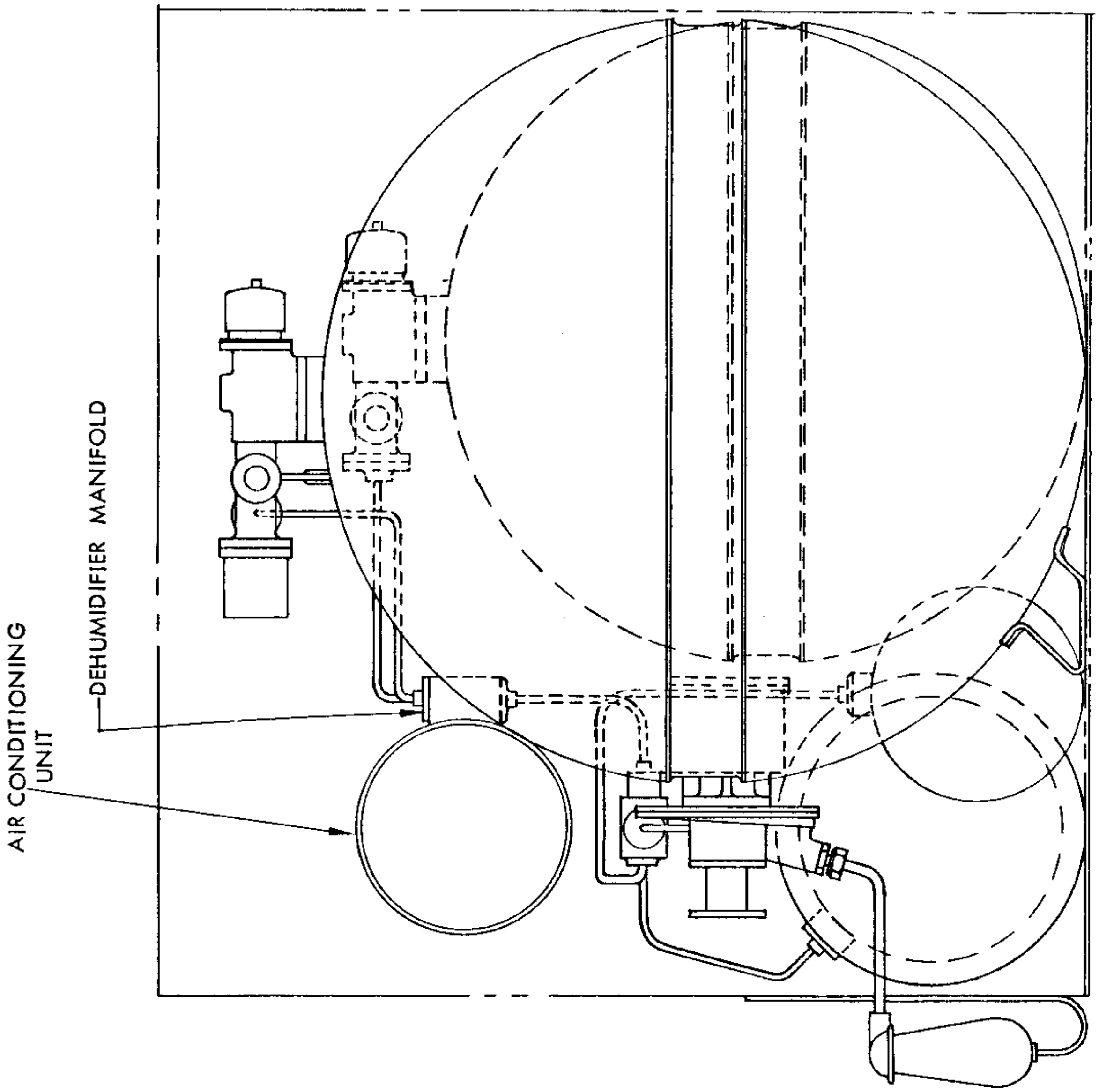


FIGURE 6-13C

INSTRUMENT PANEL

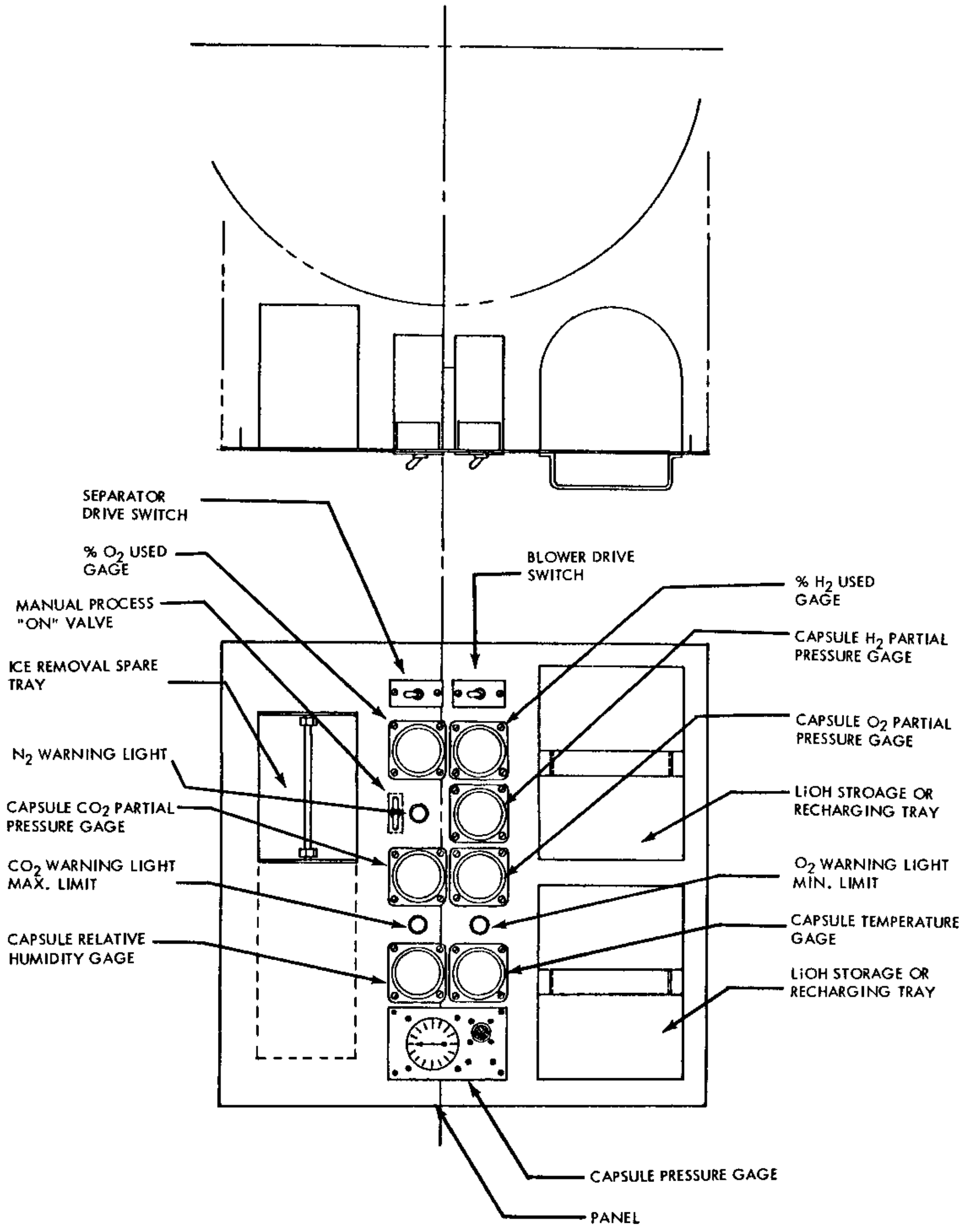


FIGURE 6-13D

APPENDIX I

METABOLIC RATE FOR AVERAGE MAN

Mary Swartz Rose summarizes the hourly expenditure in kilocalories of an average 70-kilogram (154-pound) man under various conditions as follows (ref. 2):

Sleeping	65
Awake lying still	77
Sitting at rest	100
Standing relaxed	105
Walking slowly to moderately fast	200-300
Running 5.3 mph	570
Swimming	500
Walking down stairs	364
Walking up stairs	1100
Light exercise	170
Active exercise	290
Very severe exercise	600

APPENDIX II

METABOLISM OF CHEMICAL CONSTITUENTS IN FOOD

Metabolism of Carbohydrates, e.g., Glucose

$$\begin{array}{lccccccc} & C_6H_{12}O_6 & + & 6O_2 & \rightarrow & 6CO_2 & + & 6H_2O \\ \text{Mol. Wt.} & 180 & & 192 & & 264 & & 108 \end{array}$$

The heat value of glucose = 3.74 kilocalories/gram.
O_2 consumed = 192/180 = 1.065 gram/gram glucose
CO_2 produced = 264/180 = 1.47 gram/gram glucose

Respiratory quotient = volume CO_2/volume O_2 = 6/6 = 1
H_2O produced = 108/180 = 0.6 gram H_2O/gram glucose

Metabolism of Protein

The end products of protein breakdown in the animal body include not only CO_2 and H_2O, as for carbohydrates and fats, but also the urea of the urine and certain other nitrogenous constituents of the urine and feces, as well as such compounds as urinary sulfate produced by the oxidation of sulfur containing amine acids. Hence to evaluate the contribution of protein to the total metabolism and to distinguish it from the non-protein metabolism, the analysis of urine and feces is necessary in addition to the measurement of the respiratory gas exchange.

The computation of the protein metabolism is given in reference 3 as follows:

100 grams (g) of meat protein contains:

52.38 g C   7.27 g H   22.68 g O   16.65 g N   1.02 g S

of which eliminated in the urine are:

9.405 g C   2.663 g H   14.099 g O   16.28 g N   1.02 g S

in the feces:

1.471 g C   0.212 g H   0.899 g O   0.37 g N

leaving a residium for the respiratory process of:

41.5 g C   4.4 g H   7.69 g O

Deduct intramolecular water:

0.961 g H   7.69 g O

leaving for oxidation:

41.5 g C   3.439 g H

When CO_2 is formed, 41.5 grams C unite with 110.67 grams O; = 152 grams CO_2

When H_2O is formed, 3.439 grams H unite with 27.512 grams O; = 31 grams H_2O

The heat value of protein = 4.24 kilocalories/gram

O_2 consumed = 1.382 grams/gram protein

Heat value of protein consumed = 424 kilocalories

Calorific value of O_2 = 4.34 kilocalories/liter

CO_2 produced = 1.522 grams/gram protein

Respiratory quotient = (152/44) (138/32) = 0.801

H_2O produced = (3.439 + 27.512)/100 = 0.3095 gram H_2O/gram meat protein

Metabolism of Fats (Palmitin)

$$\begin{array}{lccccc} & 2(C_{51}H_{78}O_6) & + \; 145\,O_2 & \longrightarrow & 102\,CO_2 & + \; 98\,H_2O \\ \text{M.W.} & 1612 & 4640 & & 4488 & 1764 \end{array}$$

The heat value of palmitin = 9.5 kilocalories/gram

O_2 consumed = 4640/1612 = 2.88 grams/gram palmitin

CO_2 produced = 4480/1612 = 2.78 grams/gram palmitin

R.Q. = 102/145 = 0.704

H_2O produced = 1764/1612 = 1.09 grams H_2O/gram palmitin

Examination of Theoretical Diet Prescribed

Re-examining, in the light of the preceding analyses, the theoretical diet described in Section 2.1.2:

	per day	O_2 consumed	CO_2 formed	H_2O produced by oxidation & intramolecular water
Carbohydrates	= 450 grams	480 grams	660 grams	270 grams
Proteins	= 100 grams	138 grams	150 grams	30 grams
Fats	= 75 grams	216 grams	210 grams	80 grams
	625 grams ≅ 1.38 pounds	834 grams ≅ 1.84 pounds	1020 grams ≅ 2.25 pounds	380 grams ≅ 0.84 pounds

Heat value:

450(3.74) = 1680
100(4.24) = 424
75(9.5) = 712

2816 kilocalories · (1000/252) - 11,200 Btu

Oxygen consumption:

450(1.065) = 480
100(1.382) = 138
75(2.88) = 216/834 = 1.84 pounds

CO_2 produced:

450(1.47) = 663
100(1.52) = 152
75(2.78) = 208

1023 grams = 2.26 pounds

H_2O produced:

450(0.60) = 270.0
100(0.3095) = 30.95
75(1.09) = 81.7

382.65 grams = 0.84 pound

Respiratory Quotient:

Density of CO_2 at 70°F, 1 atmosphere = 0.1145 pound/cubic foot

Density of O_2 at 70°F, 1 atmosphere = 0.0827 pound/cubic foot

$$\text{Respiratory Quotient} = \text{volume } CO_2/\text{volume } O_2 = \frac{2.26(0.0827)}{1.84(0.1145)} = 0.89$$

APPENDIX III

CAPSULE SKIN TEMPERATURE

The manned capsule will receive energy from the sun and the earth. At the same time practically all electrical and mechanical power that may be generated in the capsule will eventually be converted to thermal energy in the capsule and must be considered as part of the heat input. The capsule designer has only two general methods for dissipating this heat to space, namely by radiation into space and by the expulsion of mass from the capsule. The latter method is generally undesirable as it involves excessive weight penalties. Therefore, the radiation mechanism will be considered as the principal method of control. The skin temperature assumed by the capsule will represent a balance between the heat absorbed from the sun, the earth, and any interior power source, and the heat radiated by the external surfaces into space.

III.1 ENERGY ABSORBED FROM SUN

The amount of energy radiated to the satellite from the sun is equal to the solar constant, 1400 watts/square meter. The amount of this energy absorbed by the satellite is a function of the visual albedo of the satellite, the length of time that the satellite is exposed to the sun's rays, and the cross-sectional area of the satellite that is exposed to the sun's rays.

The visual albedo, a_v, of the satellite is a function* of the surface material and finish. For a lead carbonate white paint coated surface this value would be about 0.95, while for a titanium surface the visual albedo would have a value of about 0.2. Table III-1 presents an abbreviated list of surface characteristics for several typical materials.

TABLE III-1

CHARACTERIC PROPERTIES OF VARIOUS SURFACES

	Absorptivity $\alpha = 1-a_v$	Emissivity ϵ_{IR}	Albedo a_v
Ti	.8	.4	.2
MgO	.14	.97	.86
Al (alloy)	.35	.10	.65
Nickel (polished)	.32	.06	.68
White porcelain	.43	.90	.57
SiO over Al	.20	.23	.80
Lead Carbonate White Paint	.05	.95	.95
Tabor Surface	.90	.10	.10

The length of time that the satellite is exposed to the sun's rays is determined by the time of year, time of day, and launching angle as determined by earth system coordinates, the

---

*It is also a function of the temperature of the surface and the wavelength of the incident radiation; however, these two quantities may be considered constants.

altitude of the orbit, and the eccentricity of the orbit. For purposes of simplification, a circular orbit was assumed in this analysis. Figure III-1 shows the effect of altitude on period and velocity of a satellite in a circular orbit. The effect of time of year and time of day on the percentage of the orbital period that it is exposed to solar radiation is illustrated in Figures III-2 and III-3. Throughout the subsequent analysis the only factors considered affecting the percent of time in sunlight for an orbiting satellite are the altitude, h, and the inclination of the orbital plane to the plane of the ecliptic, β . Thus the percent of time spent in the sun for a circular orbit at a given altitude and inclination may be calculated from the following formula:

$$\mu_T = 1.0 \quad \text{when } \psi > 90 - \beta$$
$$\mu_T = (90 + \psi)/180 \text{ when } \psi > 90 - \beta \tag{1}$$

where μ_T is the eclipse factor (% time in sun) and ψ is the angle at which the satellite goes into the earth's shadow.

$$\psi = \frac{R_E}{R_E + h}$$

where R_E is the radius of earth ($\approx$ 3959 miles) and h is altitude of orbit.

The effect of altitude and orbital inclination on the eclipse factor is illustrated in Figure III-4. Eclipse factor as a function of altitude and orbital inclination is plotted in Figure III-5. Note in Figure III-5 that the eclipse factor is a double valued function of altitude. For example, at any given altitude the eclipse factor, μ_T, is either 1.0 or some value between 0.5 and 1.0 which is independent of orbital inclination, β . For an orbit lying in the plane of the ecliptic, $\beta = 0^o$, the satellite will spend a maximum of time in the shade; e.g., a 100-mile circular orbit lying in the plane of the ecliptic, $\beta = 0^o$, will have an eclipse factor $\mu_T = 0.57$ and an orbital period p = 90 minutes (see Figures III-1 and III-5). Thus the satellite will spend 43% of its orbital period or 39 minutes in the shade of the earth. For an orbit perpendicular to the plane of the ecliptic, $\beta = 90^o$, the percentage of time spent in the sunlight may vary with time of day and time of year of launching as illustrated in Figures III-2 and III-3. In the ensuing analysis, however, we will consider such polar-type orbits, $\beta = 90^o$, to be continually exposed to the sun's rays, i.e. $\mu_T = 1.0$. This would be equivalent to assuming that the polar-type orbits are launched at dawn or sunset (see Figure III-3), and at the time of the year indicated by positions 1 and 5 of Figure III-2.

The effect of satellite shape and orientation on the direct solar radiation received by the satellite is illustrated in Figures III-6 and III-7. For purposes of simplification in the subsequent analysis, the shape of the satellite is assumed to be spherical. In this case the orientation does not affect the total amount of solar radiation received, since the cross-sectional area presented to the sun's rays remains constant. The location of local hot spots on the outer skin surface, however, will depend on the orientation.

EFFECT OF ALTITUDE ON PERIOD AND VELOCITY OF SATELLITE IN A CIRCULAR ORBIT

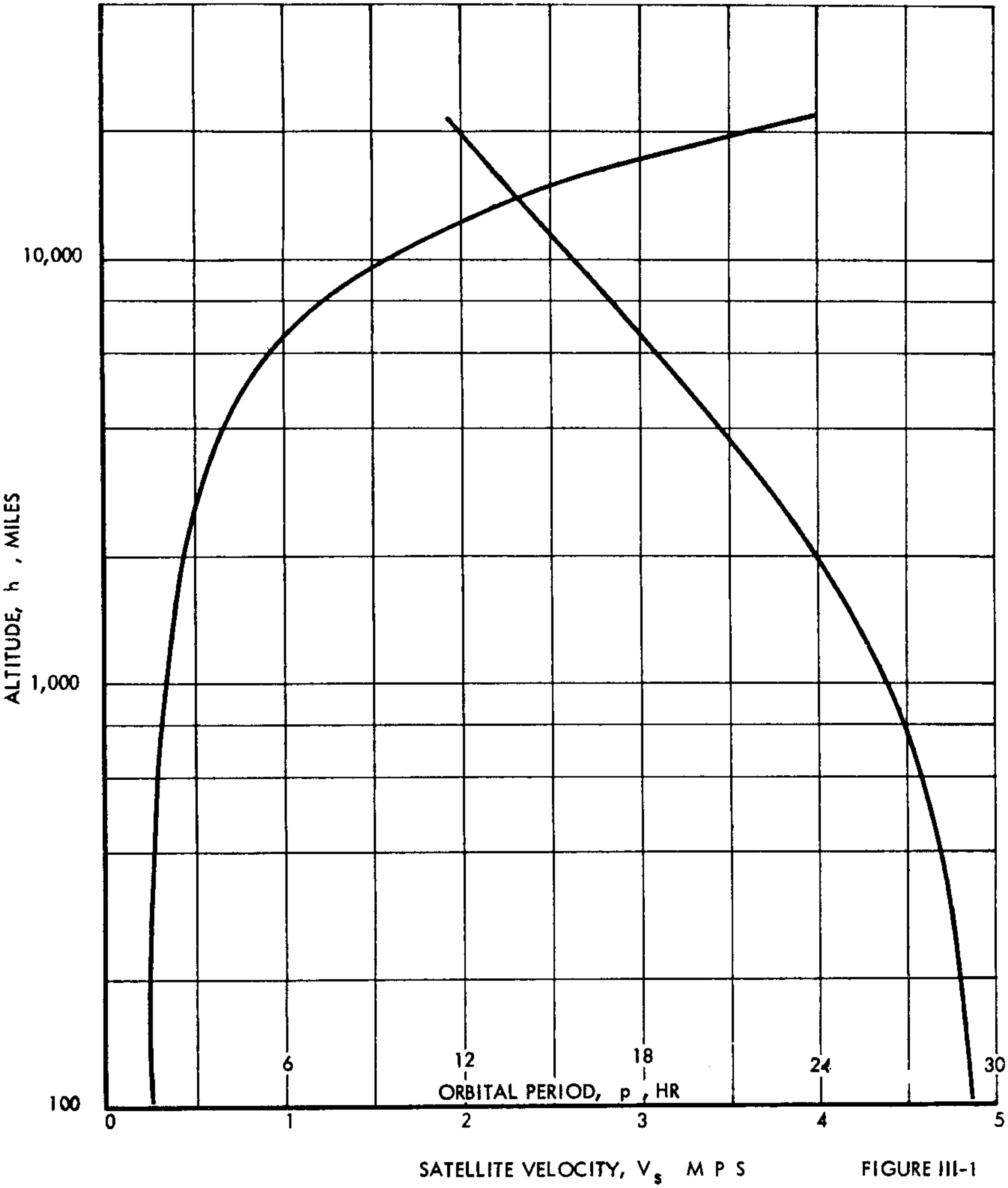
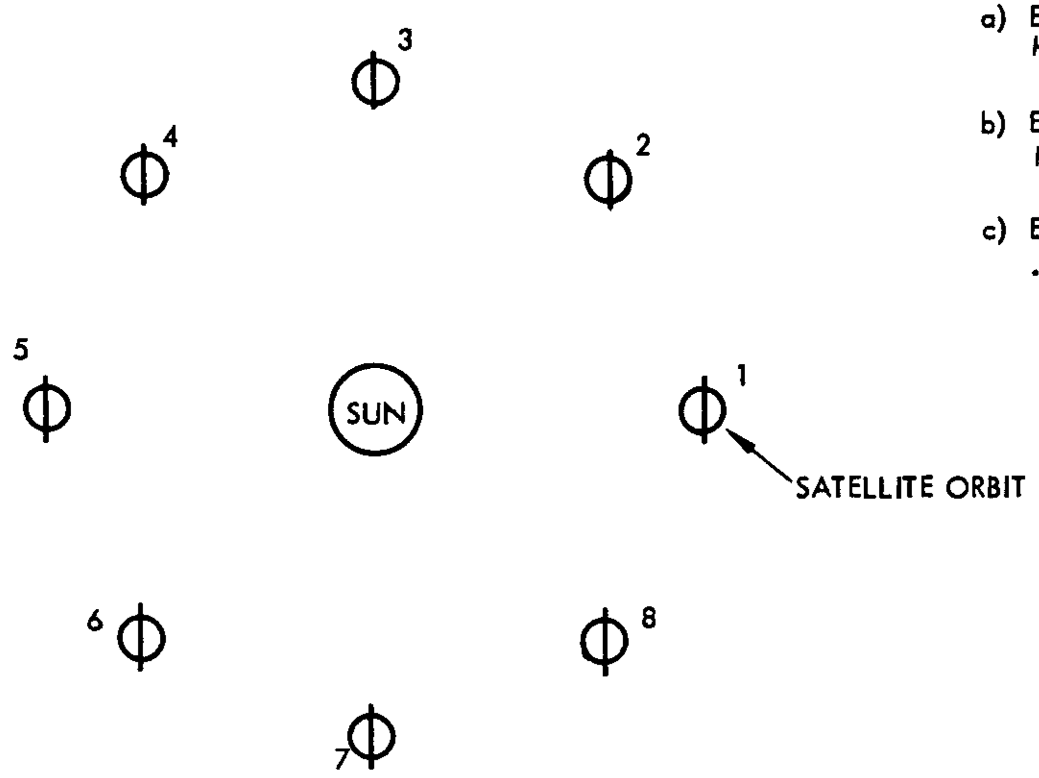


FIGURE III-1

EFFECT OF TIME OF YEAR ON ECLIPSE FACTOR



h = 100 Miles

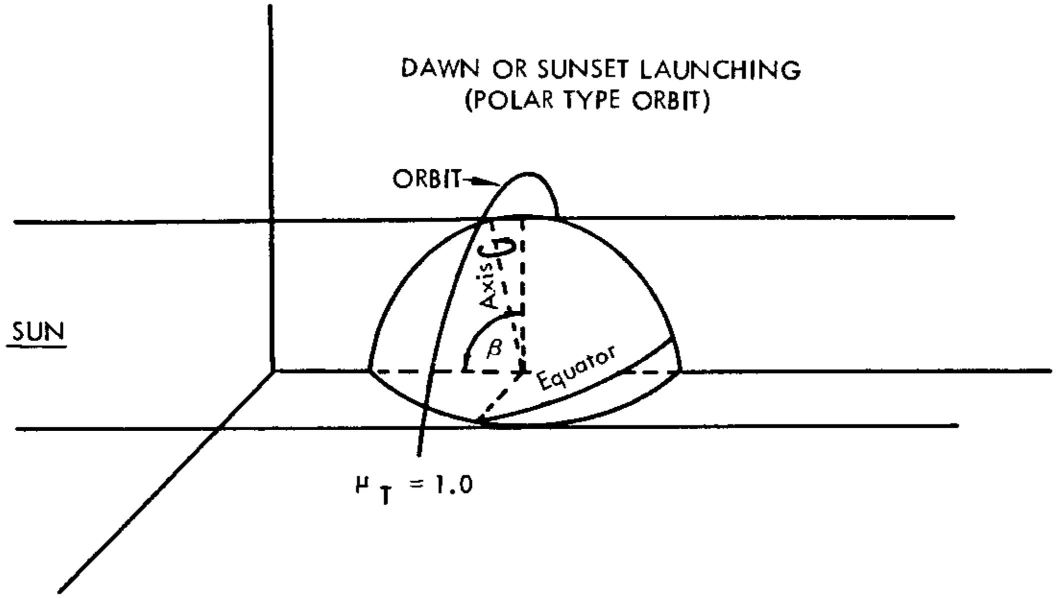
a) Earth Position - 1,5
$\mu_T = 1.0$

b) Earth Position - 3,7
$\mu_T = .571$

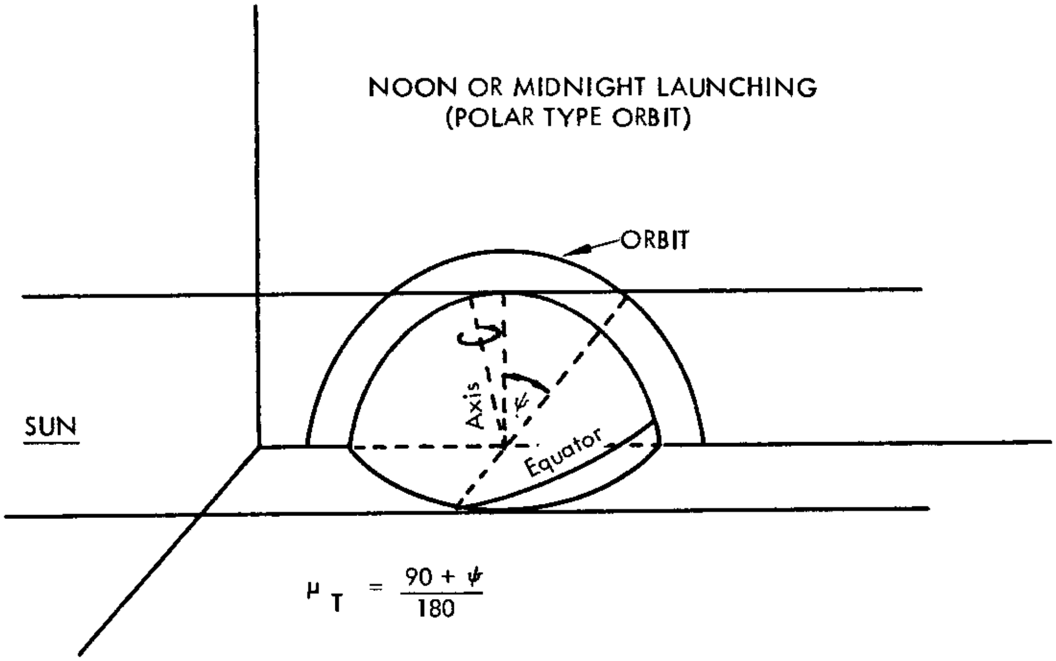
c) Earth Position - 2,4,6,8
$.571 < \mu_T < 1.0$

FIGURE III-2

EFFECT OF TIME OF DAY ON ECLIPSE FACTOR



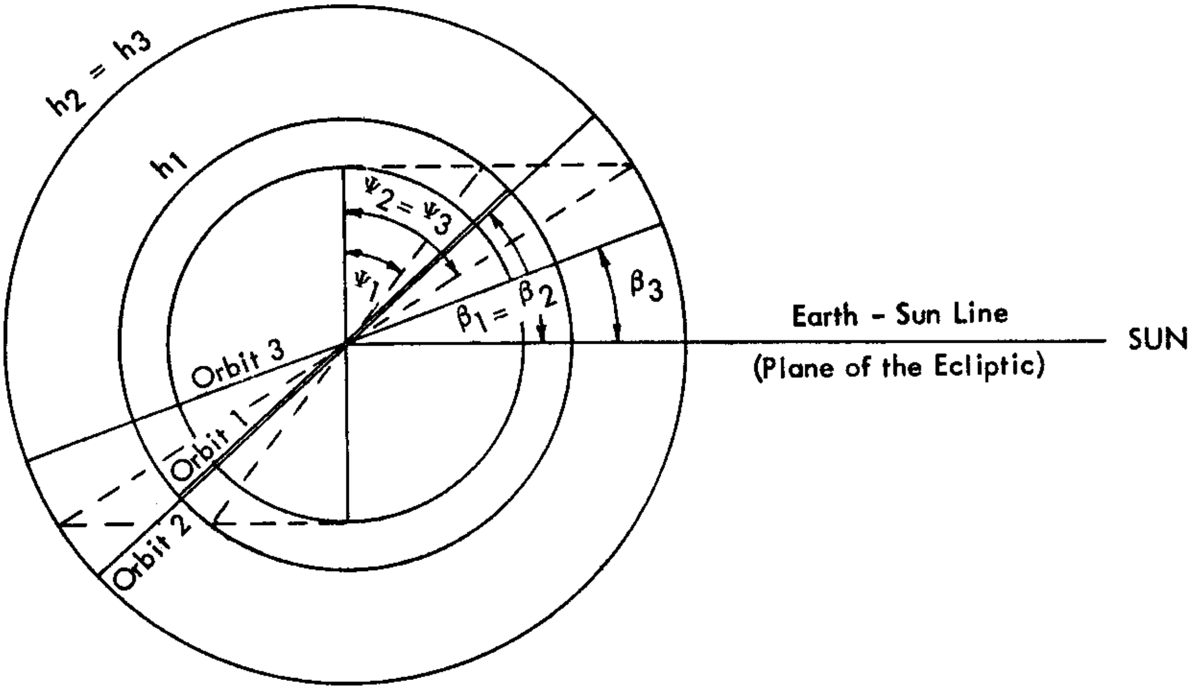
DAWN OR SUNSET LAUNCHING
(POLAR TYPE ORBIT)



NOON OR MIDNIGHT LAUNCHING
(POLAR TYPE ORBIT)

FIGURE III-3

EFFECT OF ALTITUDE AND ORBIT INCLINATION ON ECLIPSE FACTOR



ORBIT 1.

$$\Psi_1 = \cos^{-1} \frac{R_E}{R_E + h_1}$$

$$\Psi_1 < 90 - \beta_1$$

$$\mu T_1 = \frac{90 + \Psi_1}{180}$$

ORBIT 2.

$$\Psi_2 = \cos^{-1} \frac{R_E}{R_E + h_2}$$

$$\Psi_2 > 90 - \beta_2$$

$$\mu T_1 = 1.0$$

ORBIT 3.

$$\Psi_3 = \cos^{-1} \frac{R_E}{R_E + h_3} = \Psi_2$$

$$\Psi_3 < 90 - \beta_3$$

$$\mu T_3 = \frac{90 + \Psi_3}{180}$$

where:

μT = Eclipse Factor (% Time in Sun)

β = Inclination Angle of Orbit Plane to Earth Sun Line

h = Altitude

R_E = Radius of Earth (3959 Miles)

FIGURE III-4

ECLIPSE FACTOR AS A FUNCTION OF ALTITUDE AND ORBIT INCLINATION ANGLE

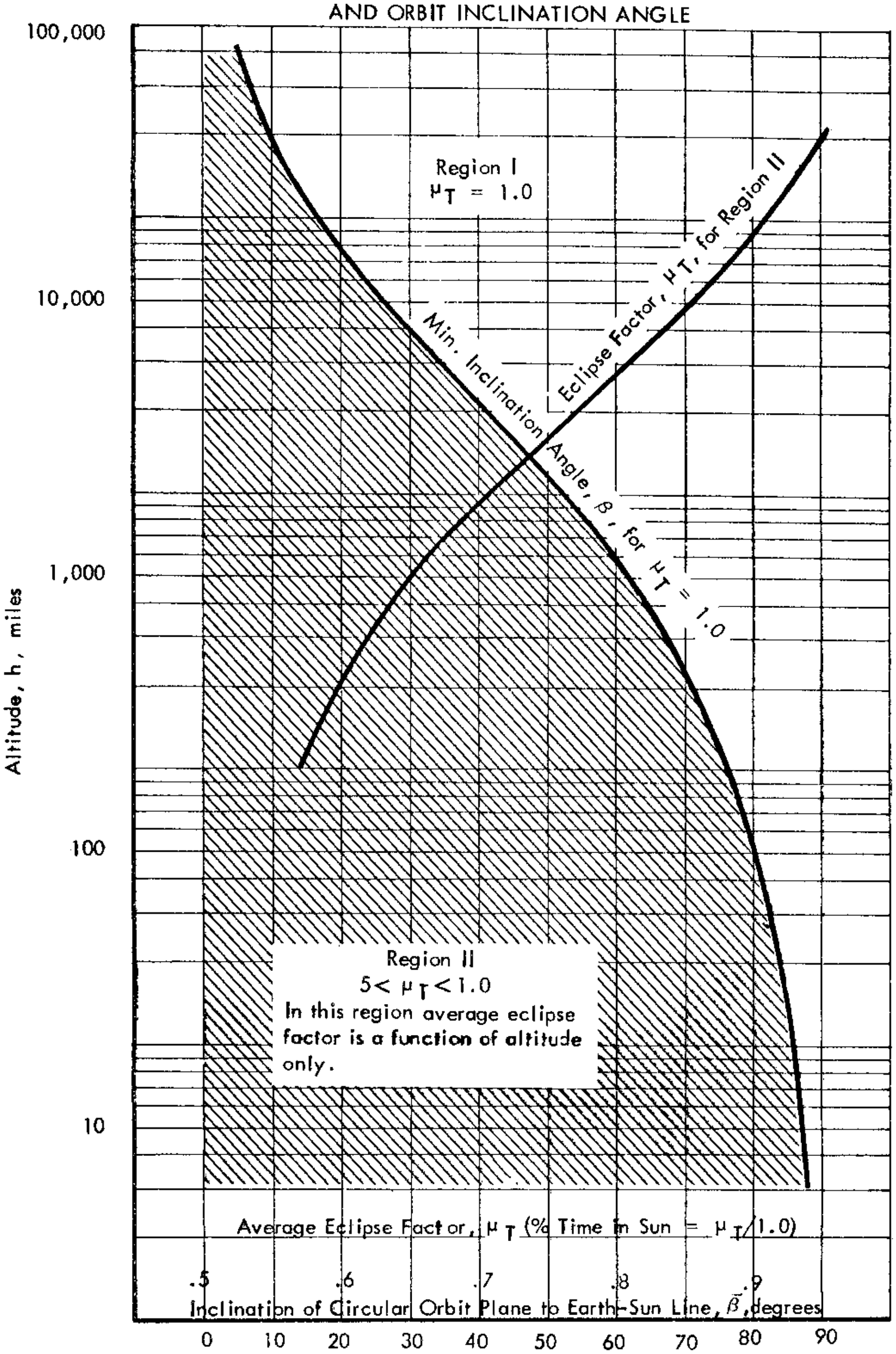
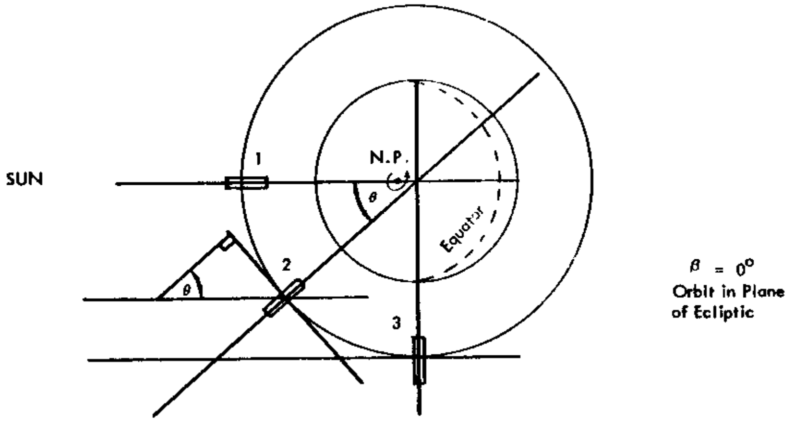


FIGURE III-5

EFFECT OF SATELLITE ORIENTATION ON DIRECT SOLAR RADIATION RECEIVED BY SATELLITE



Orbital Position

1. $\theta = 0^\circ$
   $B = 0$ (neglect end)

2. $0^\circ < \theta < 90^\circ$
   $B = 1400\,(1-a_v)\,A_c \sin\theta$

3. $\theta = 90^\circ$
   $B = 1400\,(1-a_v)\,A_c$

where:

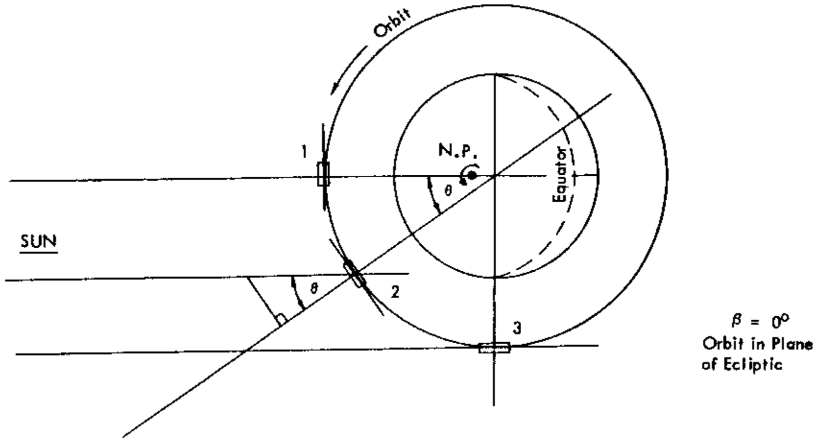
θ = Geocentric angle of satellite in orbit (measured from noon transit)

B = Direct solar radiation absorbed by satellite

A_c = Cross sectional area of cylindrical satellite (Lengthwise Projection)

FIGURE III-6

EFFECT OF SATELLITE ORIENTATION ON DIRECT SOLAR RADIATION RECEIVED BY SATELLITE



Orbital Position

1. $\theta = 0^\circ$
   $B = 1400\,(1-a_v)A_c$

2. $0^\circ < \theta < 90^\circ$
   $B = 1400\,(1-a_v)A_c \cos\theta$

3. $\theta = 90^\circ$
   $B = 0$

Note:
For a spherical shaped satellite, the overall direct solar radiation received by the satellite at any given time during the sunlit period is not a function of θ. However, the location of the hot spot on the shell of the satellite would be a function of θ.

FIGURE III-7

Thus the average solar radiation absorbed by the satellite during one revolution is

$$B = SA_c \, (1-a_v) \, \mu_T \qquad (3)$$

where S is the solar constant, 1400 watts/squaremeter, and A_c is the satellite cross-sectional area exposed to the sun's rays.

III.2 ENERGY ABSORBED FROM EARTH

The amount of energy radiated to the satellite from the earth is in the form of reflected sunlight which is in the visible wavelength range and thermal radiation which is in the infra-red range.

Reflected Sunlight

We will assume an average visual albedo for the earth, a_E, of 0.34. We will further assume that the satellite receives reflected radiation only from the earth's surface vertically below it. The reflected sunlight incident upon the satellite at any given time is

$$I_R = 1400 \, a_E \cos \theta \cos \beta \qquad (4)$$

where θ is the geocentric angle of the satellite in orbit as measured from the noon transit. The effect of variation in orbital inclination, β, and orbital position, θ, on the reflected solar radiation received by the satellite is illustrated in Figures III-8 and III-9. Since we are considering only reflection from directly beneath the satellite and since this is possible only during 1/2 the orbital period, we may integrate the term cos θ over the complete orbit considering only the positive values of cos θ and thus arrive at an average value of cos θ, e.g.:

$$\overline{\cos \theta} = \frac{\int_0^{2\pi} \cos \theta \, d\theta}{2} = \frac{2 \int_0^{\pi/2} \cos \theta \, d\theta}{2} = \frac{1}{\pi}$$

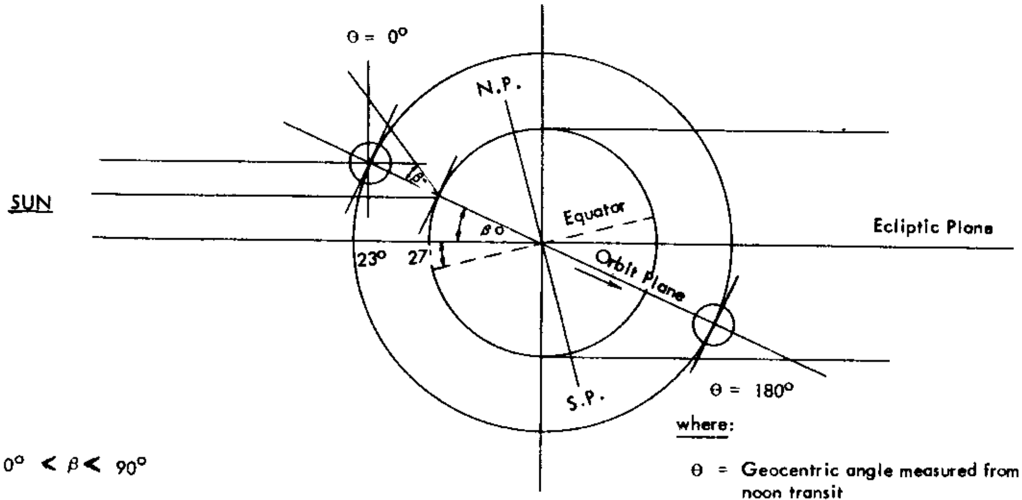
Thus the average reflected radiation absorbed by the satellite during a complete orbit is

$$C = S \, A_c \, (1-a_v) \, \frac{a_E}{\pi} \cos \beta \qquad (5)$$

Thermal Radiation

The infra-red thermal radiation from the earth may be calculated on the basis of black body radiation from the earth at 250°K, as was done in Reference 27, or by considering the combined characteristics of the earth's surface and atmosphere and calculating the long wave radiation to space from a composite of their separate characteristics, as outlined in Reference 26. In the latter case we will be taking into account the absorption of radiation of certain wavelengths by the water vapor and CO_2 in the atmosphere. A table

EFFECT OF ORBITAL INCLINATION ON REFLECTED RADIATION RECEIVED BY SATELLITE



$0° < \beta < 90°$

θ = 0° (Noon Transit Position)

$B = 1400\ (1-a_v)\ A_c$

$C = 1400\ a_e\ (1-a_v)\ A_c \cos\beta$

where:

θ = Geocentric angle measured from noon transit

β = Inclination angle of orbit plane to Earth-Sun Line

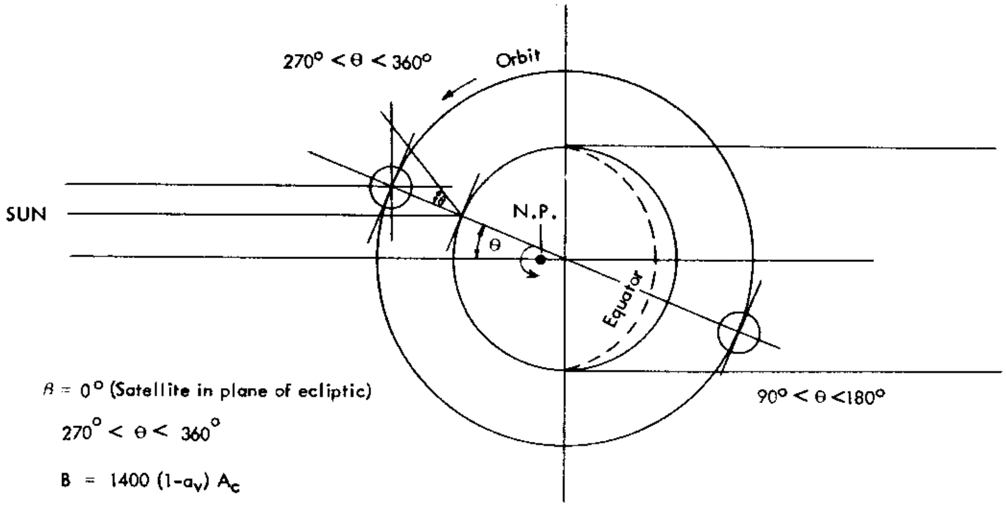
B = Direct solar radiation absorbed, watts

C = Reflected solar radiation absorbed, watts

a_e = Albedo of earth

FIGURE III-8

EFFECT OF ORBITAL POSITION ON REFLECTED RADIATION RECEIVED BY SATELLITE



β = 0° (Satellite in plane of ecliptic)

$270° < \theta < 360°$

$B = 1400\ (1-a_v)\ A_c$

$C = 1400\ a_e\ (1-a_v)\ A_c \cos\theta$

FIGURE III-9

is given in Reference 26 for infra-red radiation from the earth as a function of the earth surface temperature. Assuming an average earth surface temperature of 14°C, we have a radiation flux of 188.5 watts/square meter. Thus the average infra-red radiation absorbed by the satellite during one orbit is

$$D = 188.5\ \epsilon_{IR},\ A_c \tag{6}$$

where ϵ_{IR} = the infra-red emissivity or absorptivity of the satellite.

III.3 ENERGY BALANCE WITH NO INTERNAL POWER GENERATION

Summing up the average energy inputs to the satellite during one complete orbit and equating them to the thermal radiation from the satellite:

$$B + C + D = Q \tag{7}$$

or $SA_c(1-a_v)\,\mu_T + SA_c(1-a_v)\,\frac{a_E}{\pi}\cos\beta + 188.5\,\epsilon_{IR}A_c = \epsilon_{IR}\,A_sT_M^4$

where σ is the Stefan-Boltzmann constant, 5.67×10^{-8} watts/square meter - °K, T_M is the average equilibrium skin temperature during one complete orbit, and A_s is the surface area of the satellite (for a spherical-shaped satellite, $A_s = 4A_c$). Thus, in the absence of internal power generation, the average equilibrium skin temperature of the satellite, T_M, during one orbit is:

$$T_M = \left[\frac{(1-a_v)1400(\mu_T + \frac{.34}{\pi}\cos\beta) + \epsilon_{IR}\ 188.5}{4\ \epsilon_{IR}\ 5.67 \times 10^{-8}}\right]^{1/4} \tag{8}$$

Note that in the absence of internal power generation the average equilibrium skin temperature of the capsule is a direct function of the ratio of its absorptivity for solar radiation to its emissivity for infra-red radiation (α / ϵ_{IR}).

III.4 ENERGY BALANCE WITH INTERNAL POWER GENERATION

The heat energy input to the capsule from the generation of internal power (W) may be included in Equation 7 as follows:

$$B + C + D + W = Q \tag{9}$$

How it is transported to the radiating surface is not being considered at the moment. The average equilibrium skin temperature of the satellite during one orbit then becomes:

$$T_M = \left[\frac{(1-a_v)1400(\mu_T + \frac{.34}{\pi}\cos\beta) + \epsilon_{IR}\ 188.5 + W/A_c}{4\ \epsilon_{IR}\ 5.67 \times 10^{-8}}\right]^{1/4} \tag{10}$$

Curves of the average equilibrium skin temperature during a complete orbit as a function of the surface characteristics and internal power level are shown in Figures III-10a through 10h for a 100-mile circular orbit with the orbital plane both parallel and perpendicular to the sun's rays. An abbreviated list of materials that might be used for the outer surface was presented in Table III-1.

It will be noted that T_M in Equation 10 is no longer a direct function of the absorptivity-emissivity ratio but is now also affected inversely by the value of the infra-red emissivity coefficient.

Sample Calculation:

Consider a satellite coated with lead carbonate white paint in a 100-mile circular orbit where the plane of the orbit lies in the plane of the ecliptic. Let the diameter of the spherical-shaped satellite equal 2 meters and assume an internal heat generation of 3.4 kilowatts:

$h = 100$ miles
$\psi = \cos^{-1} R_E/(R_E + h) = \cos^{-1} (3959/4059) = 12.74^\circ$
$\beta = 0^\circ$
$\psi < 90 - \beta$
$\mu_T = (90 + \psi)/180 = 102.74/180 = 0.571$
$A_c = \pi d_o^2/4 = \pi\, 4/4 = \pi = 3.1416$ square meters
$W/A_c = 3400/3.1416 = 1080$ watts/square meter
$a_v = 0.95$
$\epsilon_{IR} = 0.95$

$$T_M = \left[\frac{(1 - .95)\ 1400\ (.571 + \frac{.34}{\pi}) + .95(188.5) + 1080}{4(.95)\ 5.67 \times 10^{-8}}\right]^{1/4}$$

$$= 280^\circ K = 44^\circ F$$

This may be compared with a temperature of -136°F which would be the resulting average equilibrium skin temperature for the case described in the absence of internal heat generation. The example chosen for this sample calculation is a limiting case of the maximum allowable internal heat generation that can be handled solely by adjustment of the outer surface characteristics (see Figure III-11). Heat loads in excess of this will require additional refrigeration equipment.

III.5 CYCLIC VARIATIONS IN SKIN TEMPERATURE

The magnitude of possible variations in the outer skin temperature may be calculated on the basis of the average equilibrium skin temperature in the sun or in the earth's shadow.

AVERAGE EQUILIBRIUM SKIN TEMPERATURE
DURING ONE COMPLETE ORBIT AS A FUNCTION OF
SURFACE CHARACTERISTICS AND INTERNAL POWER LEVEL

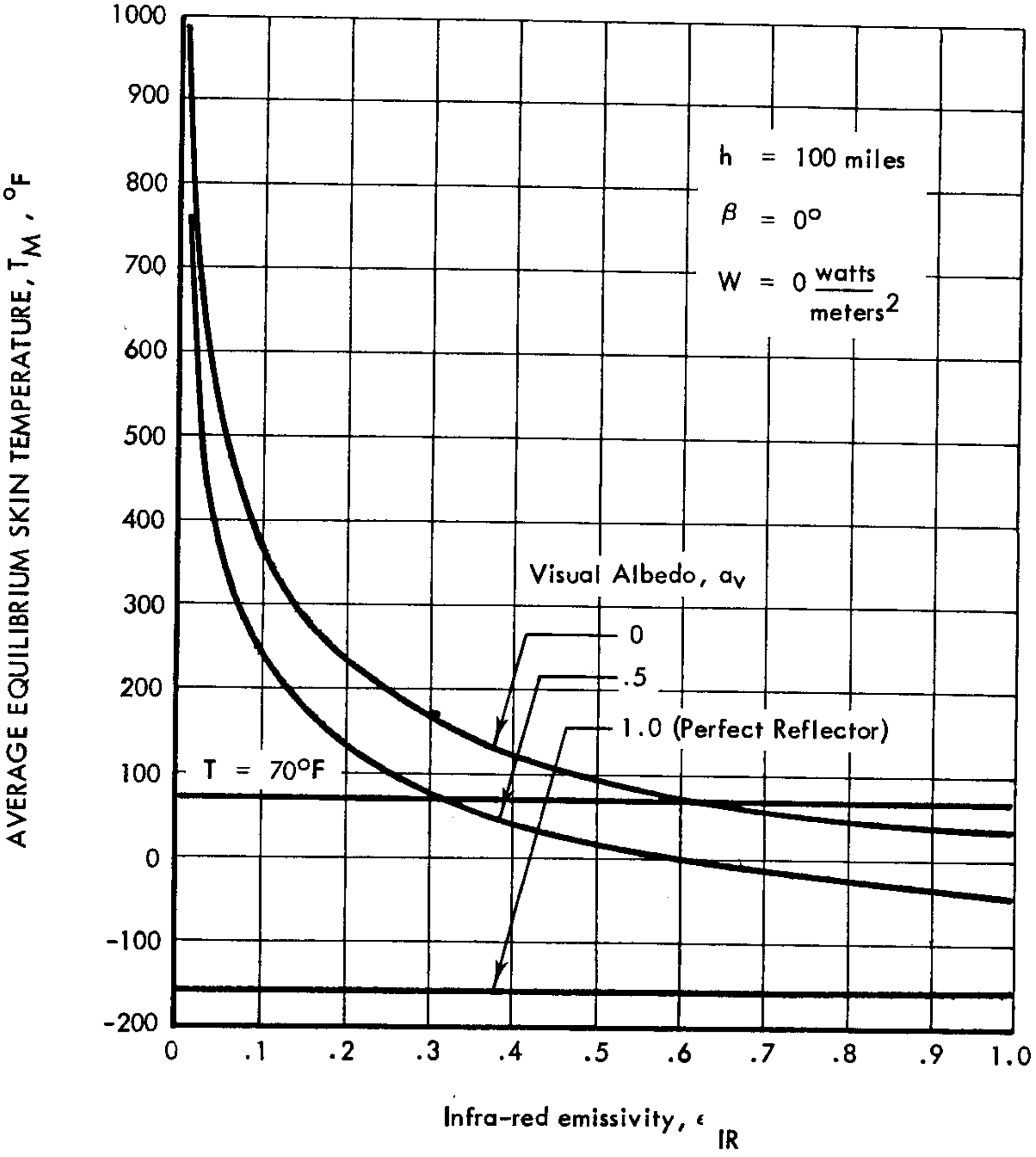


FIGURE III-10a

AVERAGE EQUILIBRIUM SKIN TEMPERATURE DURING ONE COMPLETE ORBIT AS A FUNCTION OF SURFACE CHARACTERISTICS AND INTERNAL POWER LEVEL

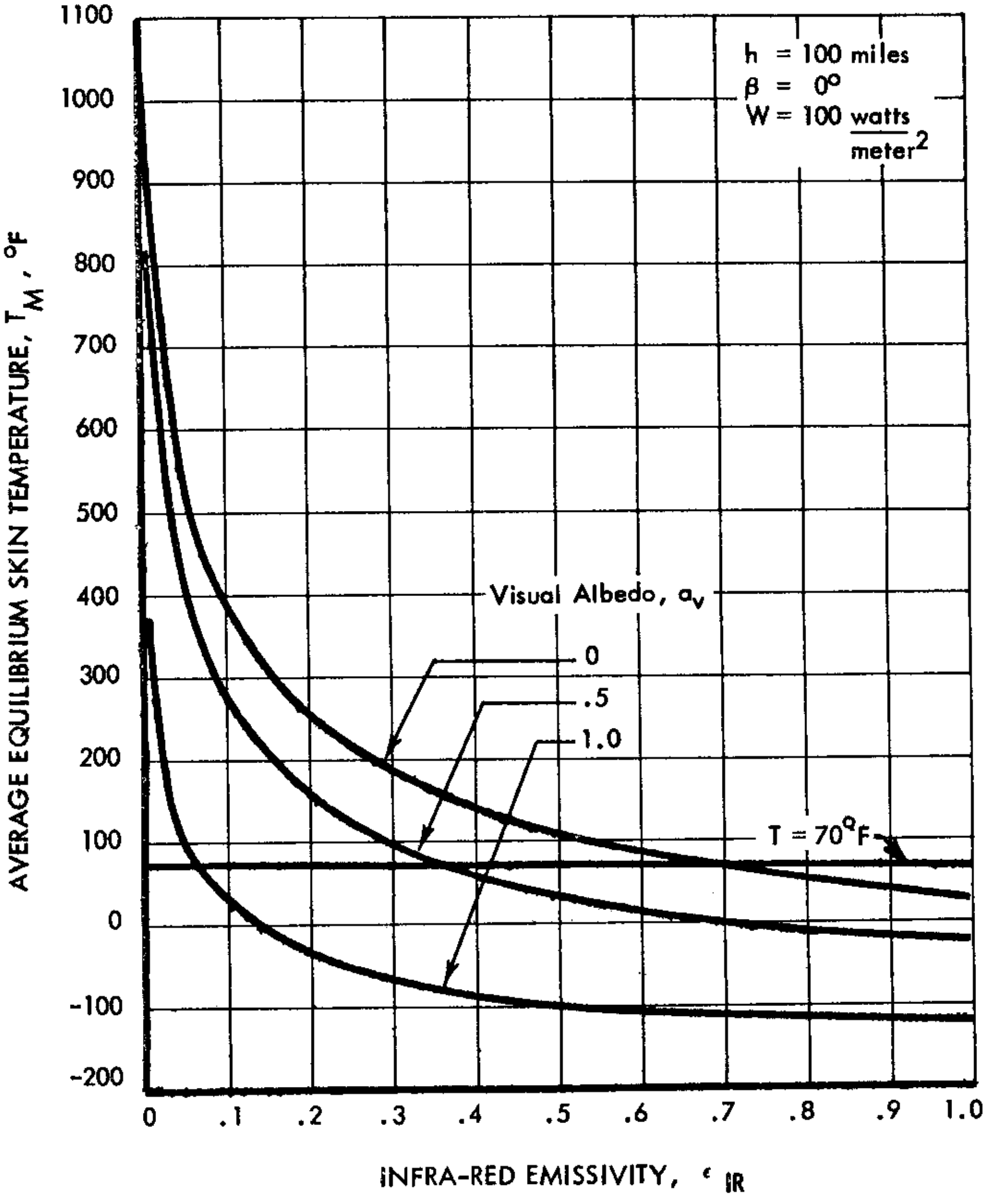


FIGURE III-10b

AVERAGE EQUILIBRIUM SKIN TEMPERATURE DURING ONE COMPLETE ORBIT AS A FUNCTION OF SURFACE CHARACTERISTICS AND INTERNAL POWER LEVEL

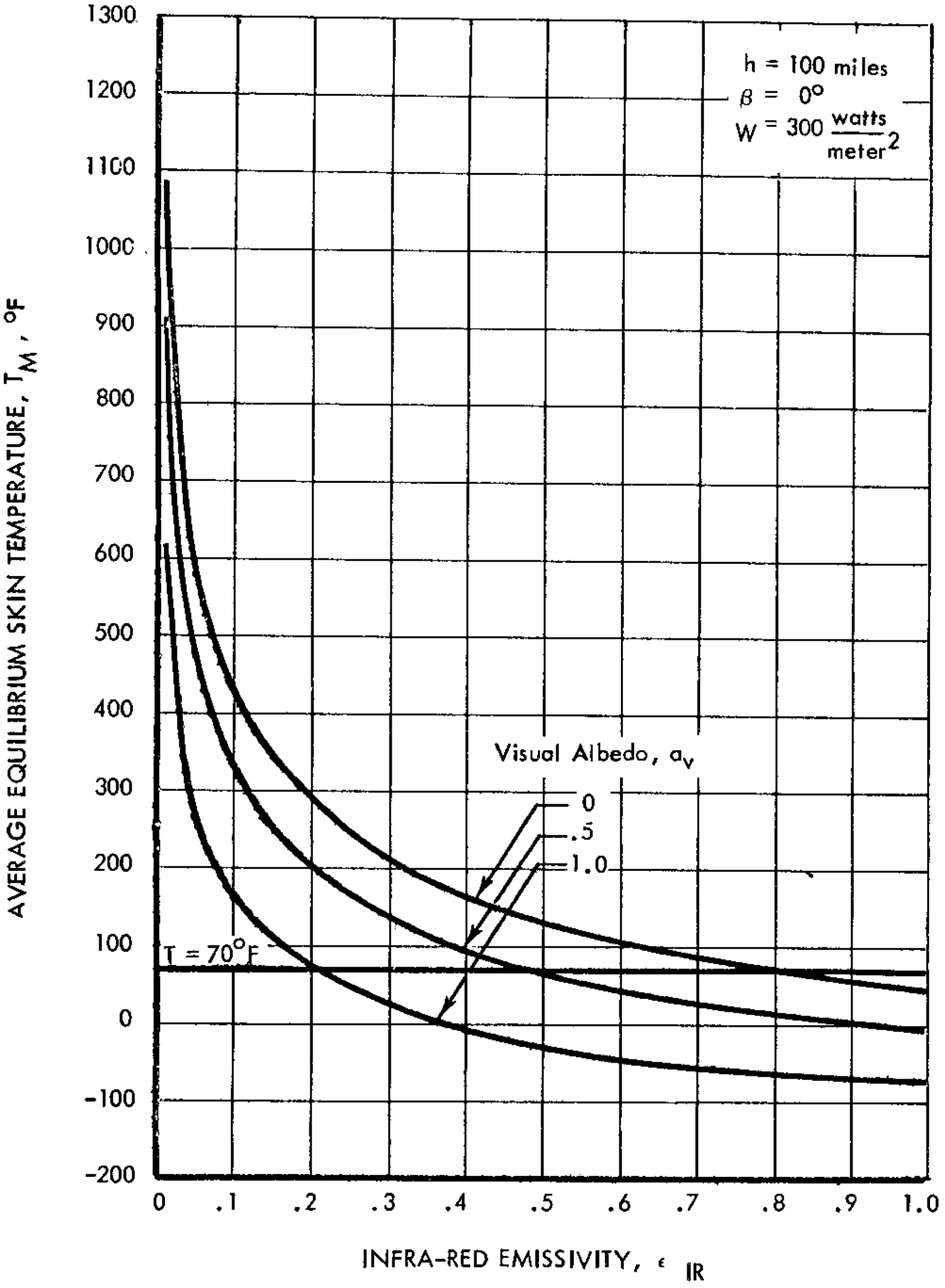


FIGURE III-10c

AVERAGE EQUILIBRIUM SKIN TEMPERATURE DURING ONE COMPLETE ORBIT AS A FUNCTION OF SURFACE CHARACTERISTICS AND INTERNAL POWER LEVEL

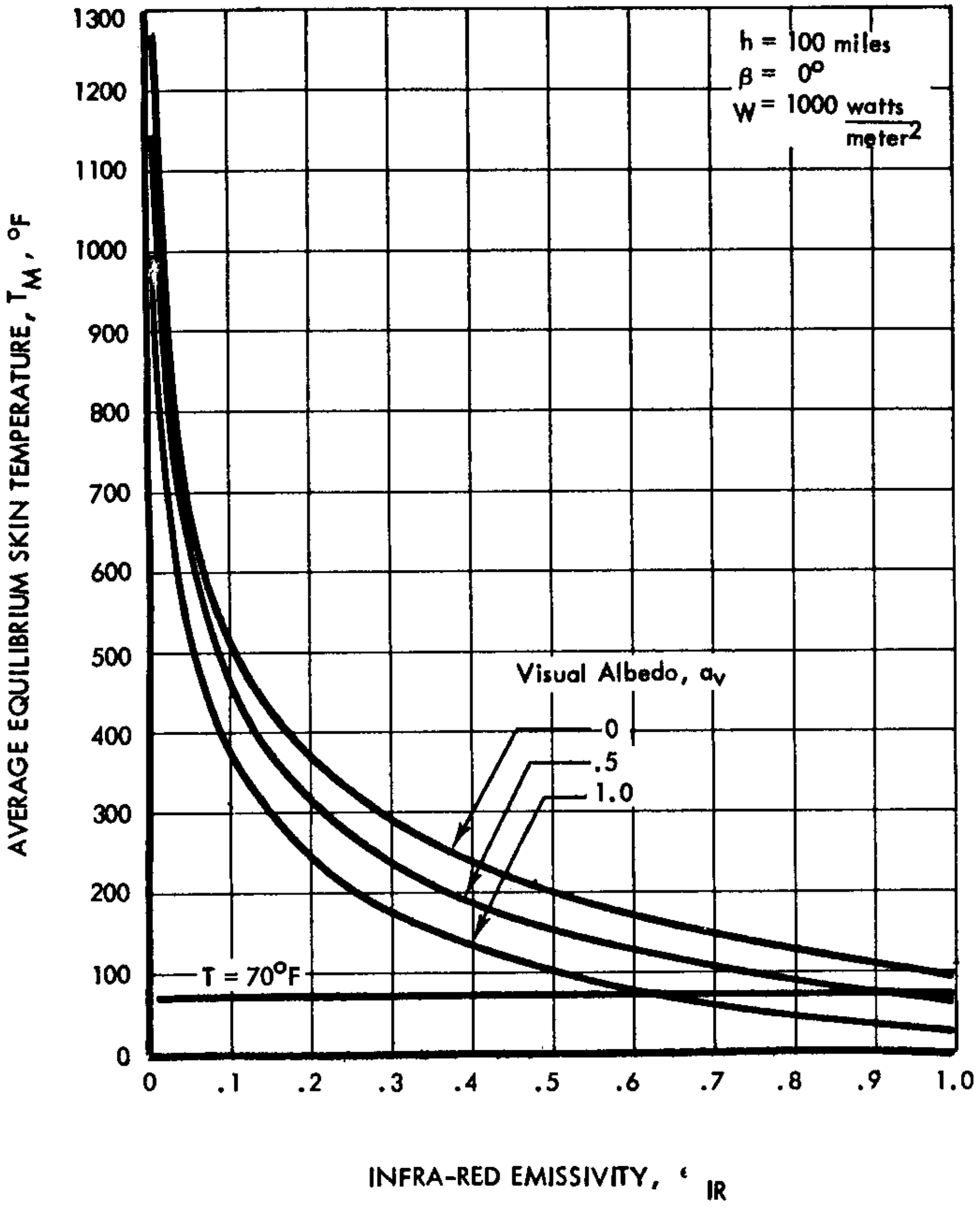


FIGURE III-10d

AVERAGE EQUILIBRIUM SKIN TEMPERATURE DURING ONE COMPLETE ORBIT AS A FUNCTION OF SURFACE CHARACTERISTICS AND INTERNAL POWER LEVEL

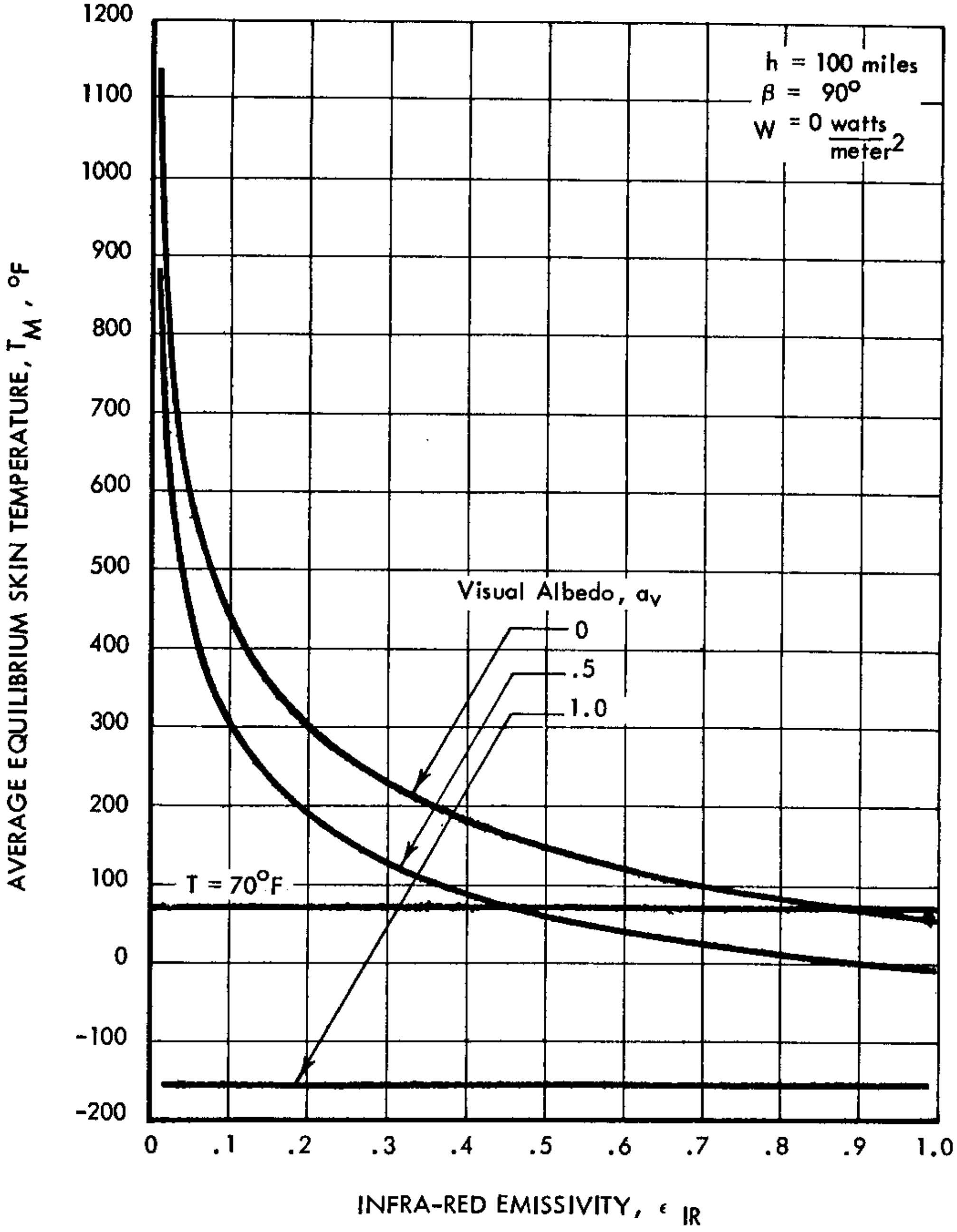


FIGURE III-10e

AVERAGE EQUILIBRIUM SKIN TEMPERATURE DURING ONE COMPLETE ORBIT AS A FUNCTION OF SURFACE CHARACTERISTICS AND INTERNAL POWER LEVEL

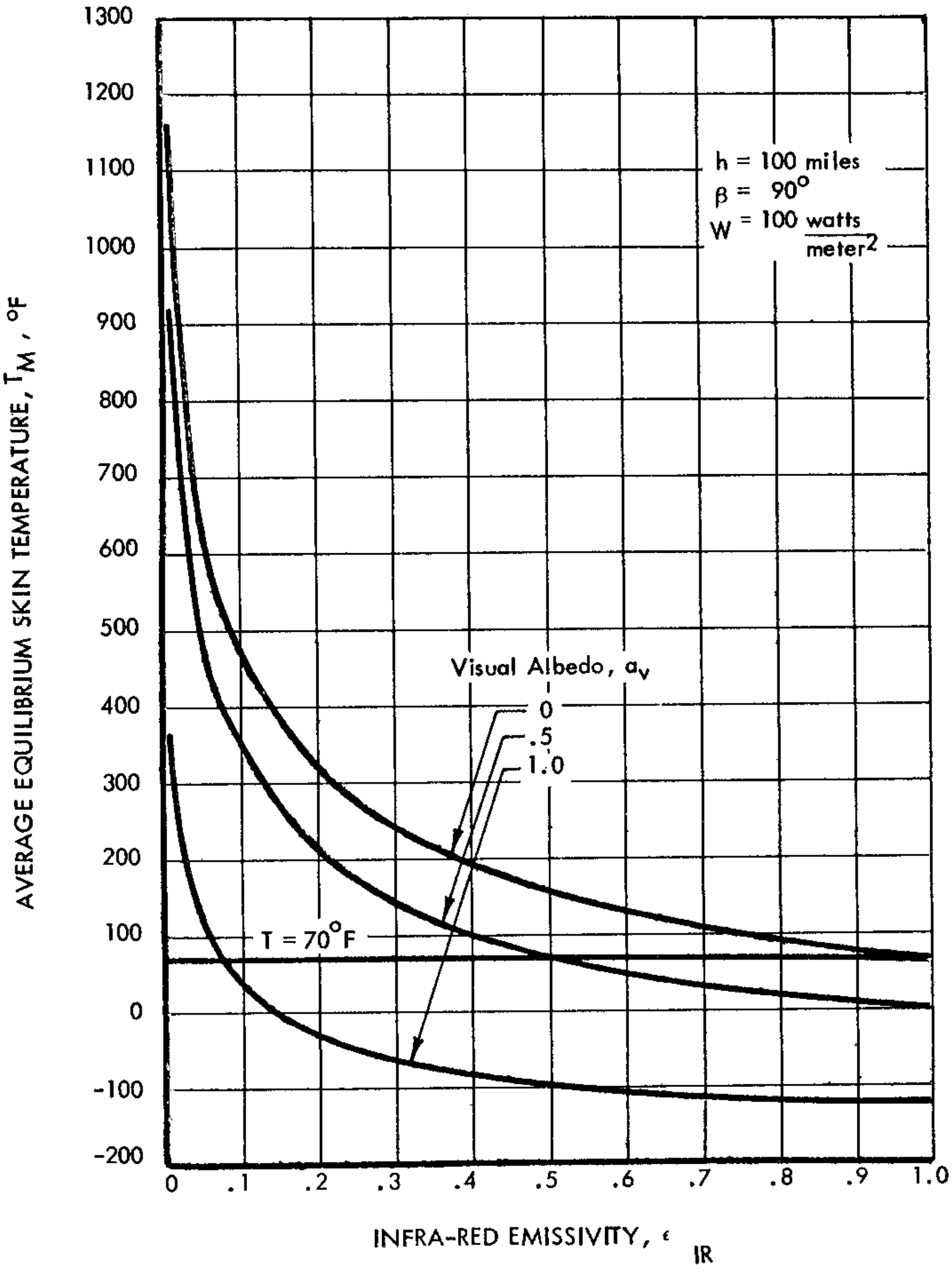


FIGURE III-10f

AVERAGE EQUILIBRIUM SKIN TEMPERATURE DURING ONE COMPLETE ORBIT AS A FUNCTION OF SURFACE CHARACTERISTICS AND INTERNAL POWER LEVEL

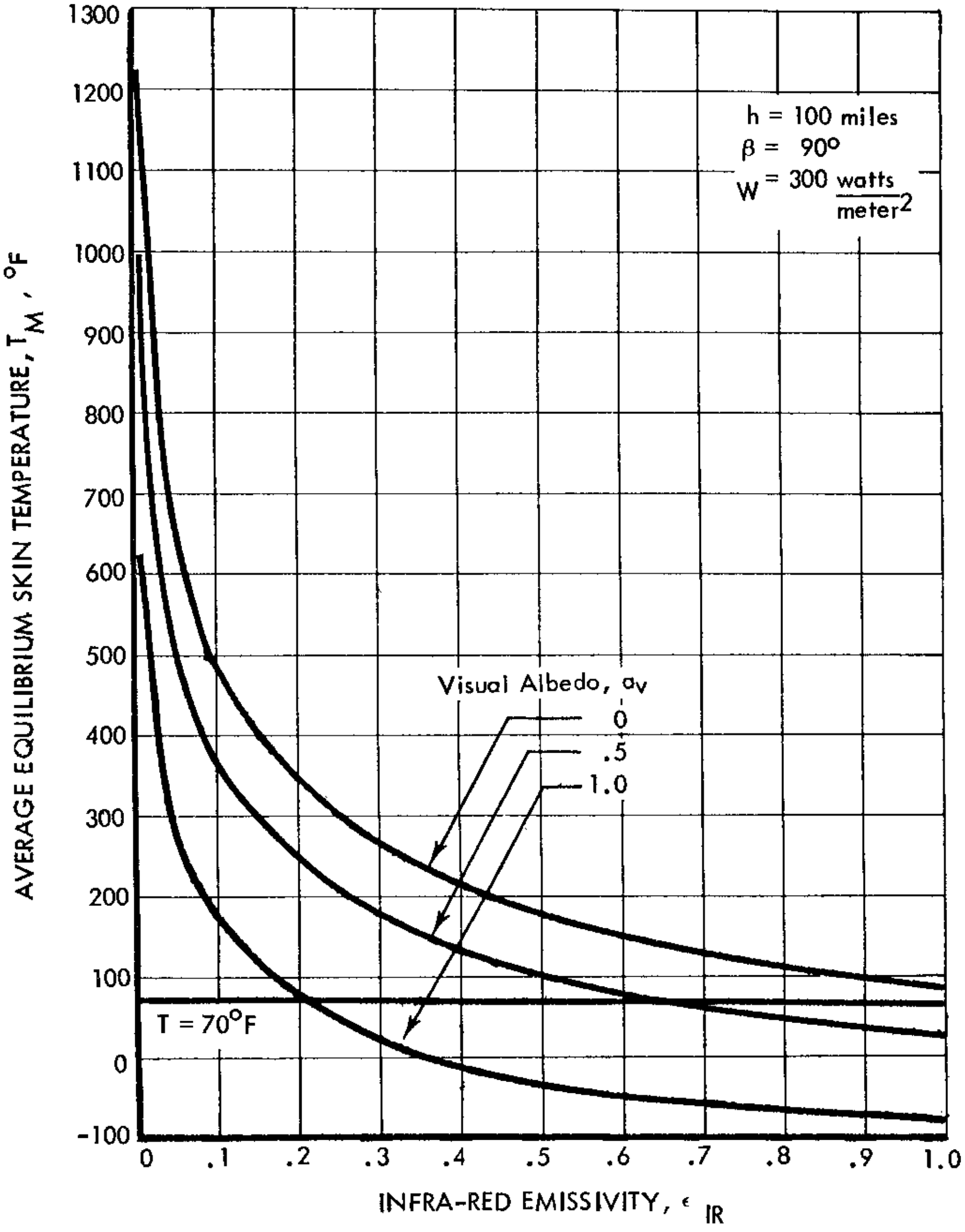


FIGURE III-10g

AVERAGE EQUILIBRIUM SKIN TEMPERATURE DURING ONE COMPLETE ORBIT AS A FUNCTION OF SURFACE CHARACTERISTICS AND INTERNAL POWER LEVEL

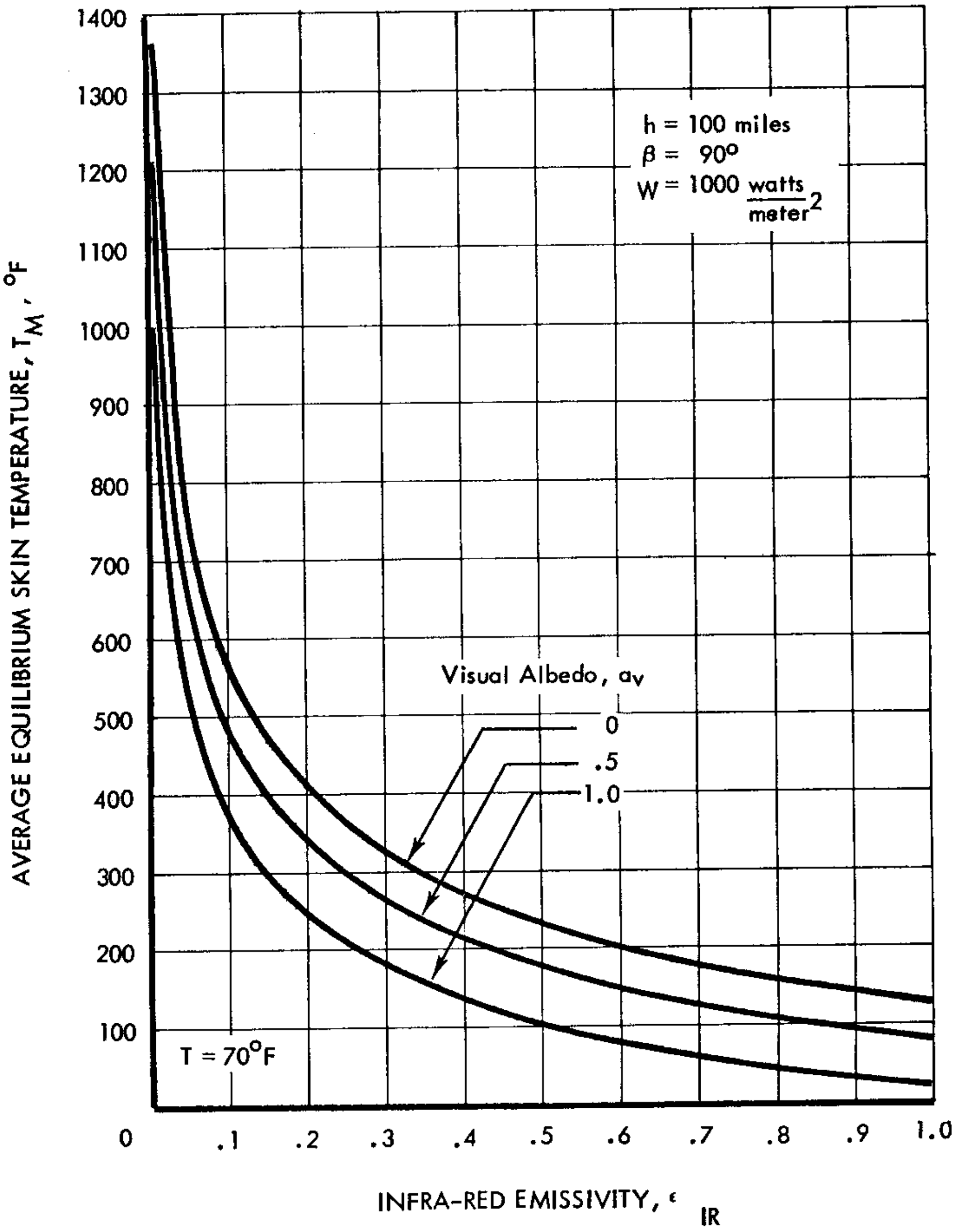
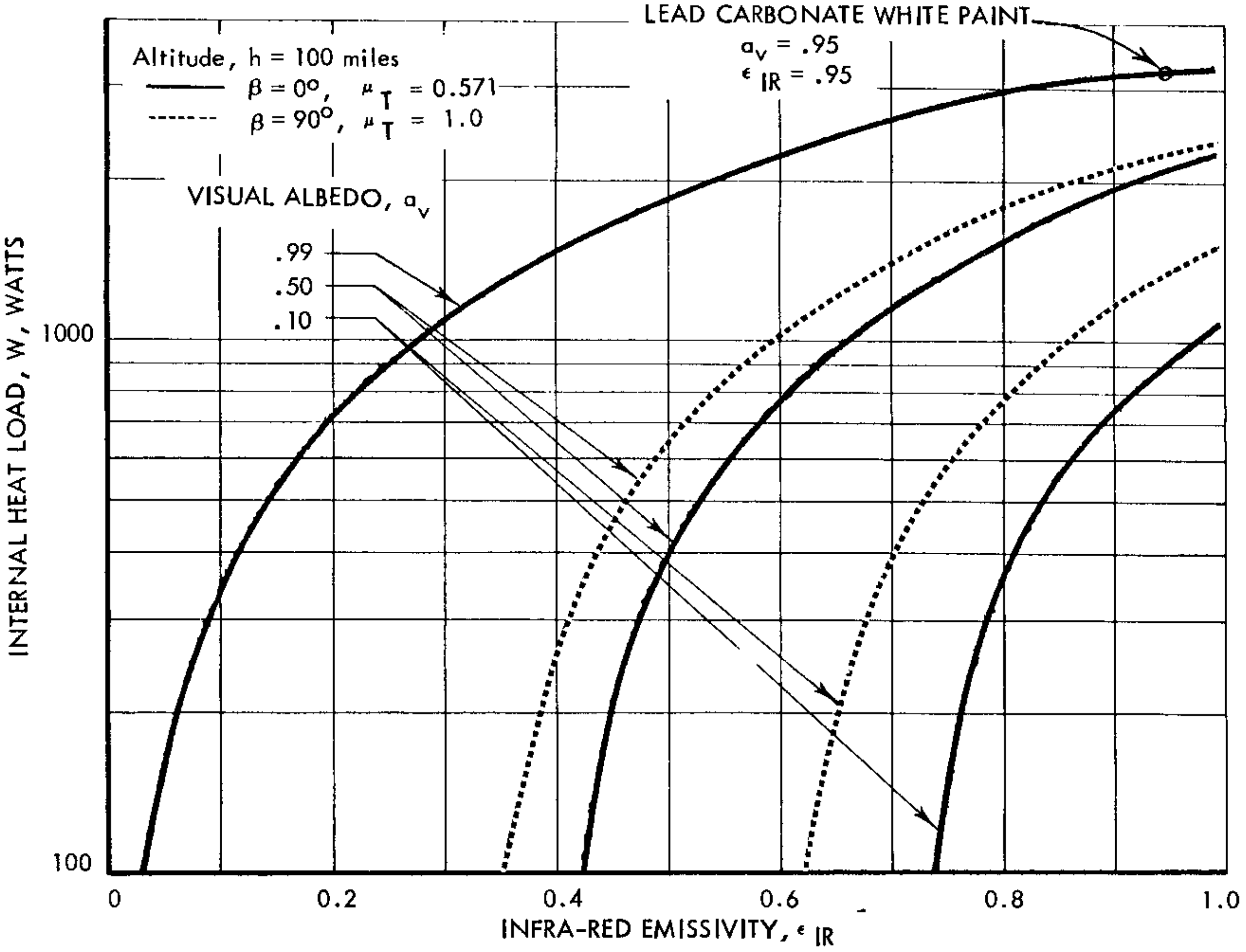


FIGURE III-10h

ALLOWABLE INTERNAL HEAT LOAD AS A FUNCTION OF SURFACE CHARACTERISTICS AND A 44°F AVERAGE EQUILIBRIUM SKIN TEMPERATURE DURING ONE COMPLETE ORBIT



ASSUMPTIONS:

1. Average Equilibrium Skin Temperature = 44°F (One Complete Orbit)
2. Heat Capacity of Skin Neglected
3. Uniform Temperature Distribution
4. Solar Constant = 1400 watts/meter^2
5. Earth Albedo = .34
6. Earth Thermal Radiation = 188.5 watts/meter^2
7. Spherical Shaped Capsule
8. Radius = 1 Meter

FIGURE III-11

For the sunlit portion of the orbit the average equilibrium temperature is:

$$T_M = \left[\frac{(1-a_v)1400(1.0 + \frac{2a_E}{\pi}) + \epsilon_{IR}\, 203.4 + W/A_c}{4 \quad {}_{IR}\, 5.67 \times 10^{-8}} \right]^{1/4} \qquad (11)$$

where the term involving reflected radiation is now averaged over only one-half the orbit and the thermal radiation flux from earth is now based on an average daylight earth surface temperature of 24°C.

During the shaded portion of the orbit there are only two energy inputs involved in the heat balance equation, i.e., the internal heat load and the thermal energy radiated from earth. Since both of these quantities may be considered constant, the equilibrium temperature is assumed constant throughout this interval. Thus the average equilibrium skin temperature during the shaded portion of the orbit is

$$T_{MIN} = \left[\frac{\epsilon_{IR}\; 175.2 + W/A_c}{4\, \epsilon_{IR}\, 5.67 \times 10^{-8}} \right]^{1/4} \qquad (12)$$

where the thermal radiation flux from the earth is based on an average night time earth surface temperature of 4°C.

Applying Equations 9 and 10 to the example previously considered in the sample calculation, we obtain:

$$T_{MAX} = \left[\frac{(1 - .95)1400(1.0 + .216) + .95(203.4) + 1080}{4(.95)\; 5.67 \times 10^{-8}} \right]^{1/4}$$

$$= 282^{\circ}K = 48^{\circ}F$$

$$T_{MIN} = \left[\frac{(.95)(175.2) + 1080}{4(.95)\; 5.67 \times 10^{-8}} \right]^{1/4}$$

$$= 276^{\circ}K = 37^{\circ}F$$

In this example the internal heat generated is seen to have a significant stabilizing effect upon the variation in skin temperature experienced during one orbit. Since the period the satellite spends in either sunlight or shadow is relatively short (approximately 45 minutes) the thermal capacity of the shell will have a further stabilizing effect. Curves of the average equilibrium skin temperature during sunlit and shaded portions of the orbit as a function of surface characteristics and internal power level are shown in Figures III-12 and III-13 for a 100-mile circular orbit with the orbital plane lying in the plane of the ecliptic.

III.6 DISCUSSION OF RESULTS

In analyzing the complicated temperature control problem, several simplifying assumptions were made and certain factors not considered in detail, since to do so would require a major effort on just this section alone. The ensuing discussion is an attempt to cover the more salient points of omission in the preceding analysis.

For purposes of simplification, all of the preceding analysis was conducted with reference to a spherical-shaped capsule. Since the average satellite temperature is directly affected by the ratio of projected area to surface area, the shape must be taken into account when considering a particular satellite. In Reference 27 the comparison is made between a cylindrical-conical shaped satellite and a sphere. Depending upon orientation, the cylindrical-conical shaped capsule is shown to achieve an average temperature 30° to 40°K higher than the sphere.

Throughout the analysis, the assumption was made that the entire shell surface is at the same temperature. The justification for this assumption will depend on three factors: (1) the internal heat load may be applied to the outer shell so as to produce a uniform temperature distribution; (2) the satellite may rotate, thus producing a uniform temperature distribution; (3) the rate of heat conduction through the material of the shell may allow for a uniform temperature distribution. The latter point is examined in detail in Reference 28 for the steady-state case of a spherical-shaped aluminum alloy satellite with negligible internal heat load. Temperature distribution in the shell is plotted as a function of R^2/t, where R is the radius of the shell in inches and t is the thickness in inches. For a value of $R^2/t = 10^4$ the maximum variation from the surface temperature based on infinite conduction is ±20%. This variation decreases exponentially as $R^2/t \rightarrow 0$. For the size satellite considered in our sample calculation, $d_o = 2$ meters, an aluminum shell 1/8 inch thick would be affected to this order of magnitude.

The problem of transient conditions is examined in Reference 26 for the spherical-shaped satellite. This analysis validates the calculation of the average equilibrium temperature based on the average of the day and night radiation received by the satellite. The problem is analyzed in more detail for a cylindrical-shaped satellite in Reference 29. In this case, extreme variations between -150° to 380°F are encountered on the sunlit end of a 0.020-inch titanium skin cylinder that is stabilized with one end facing the sun. The variations are cyclic over a period of 1-1/2 hours. The variations of mean skin temperature for the cylinder sides, however, are kept to within ±120°F of the average temperature for one orbit. The orbit in this case is in the plane of the ecliptic, which is the case resulting in the most extreme range. The conclusions of this analysis are that the smaller the ratio of absorptivity to emissivity, the lower the mean skin temperature and the smaller the cyclic variation. Also for a given ratio of α/ϵ_{IR}, the smaller the individual values of α and ϵ_{IR}, the less the temperature variation becomes. Internally generated heat was not considered in this analysis.

AVERAGE EQUILIBRIUM SKIN TEMPERATURES DURING SUNLIT PORTION OF ORBIT AS A FUNCTION OF SURFACE CHARACTERISTICS AND INTERNAL POWER LEVEL

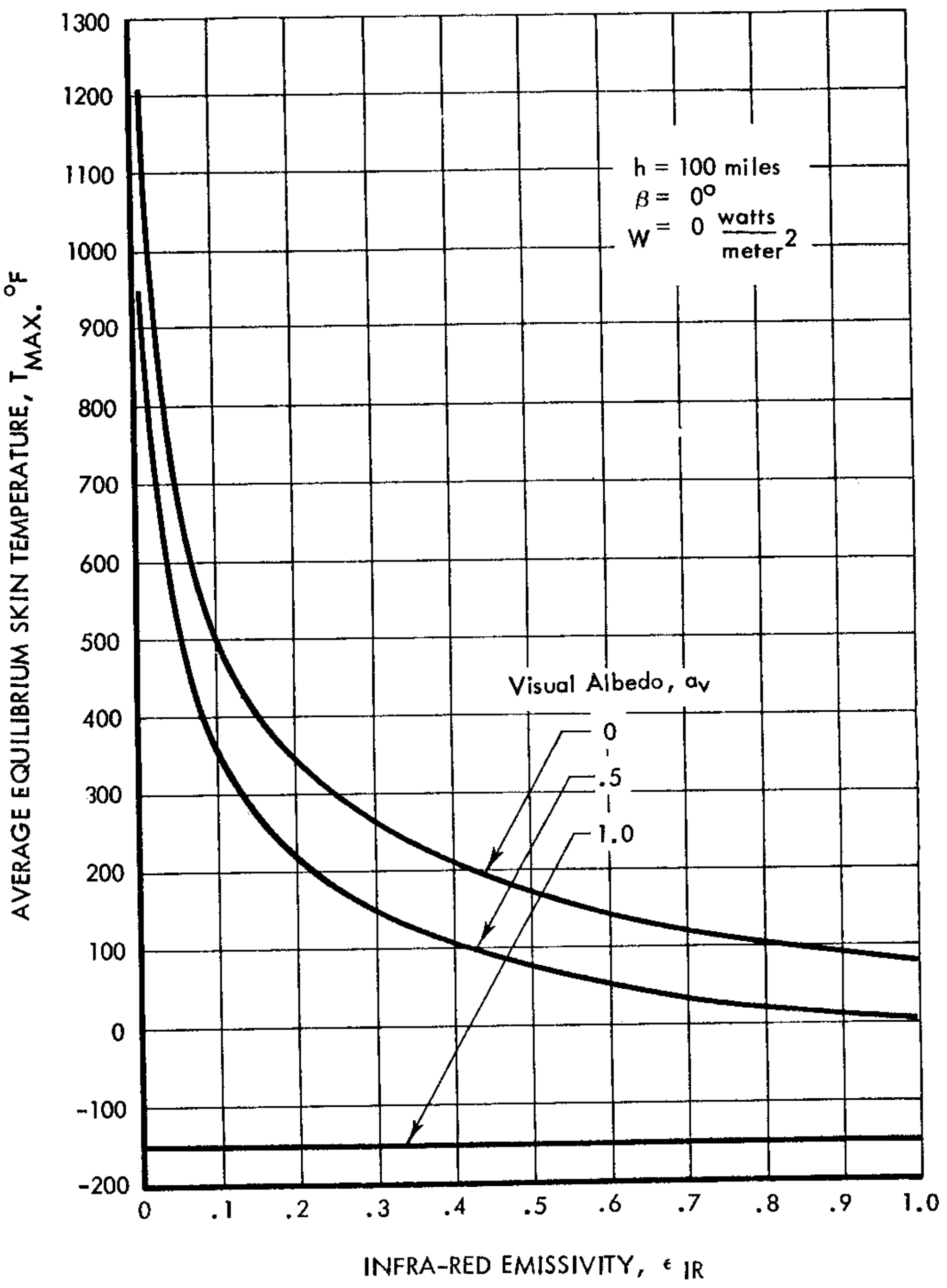


FIGURE III-12a

AVERAGE EQUILIBRIUM SKIN TEMPERATURES DURING SUNLIT PORTION OF ORBIT AS A FUNCTION OF SURFACE CHARACTERISTICS AND INTERNAL POWER LEVEL

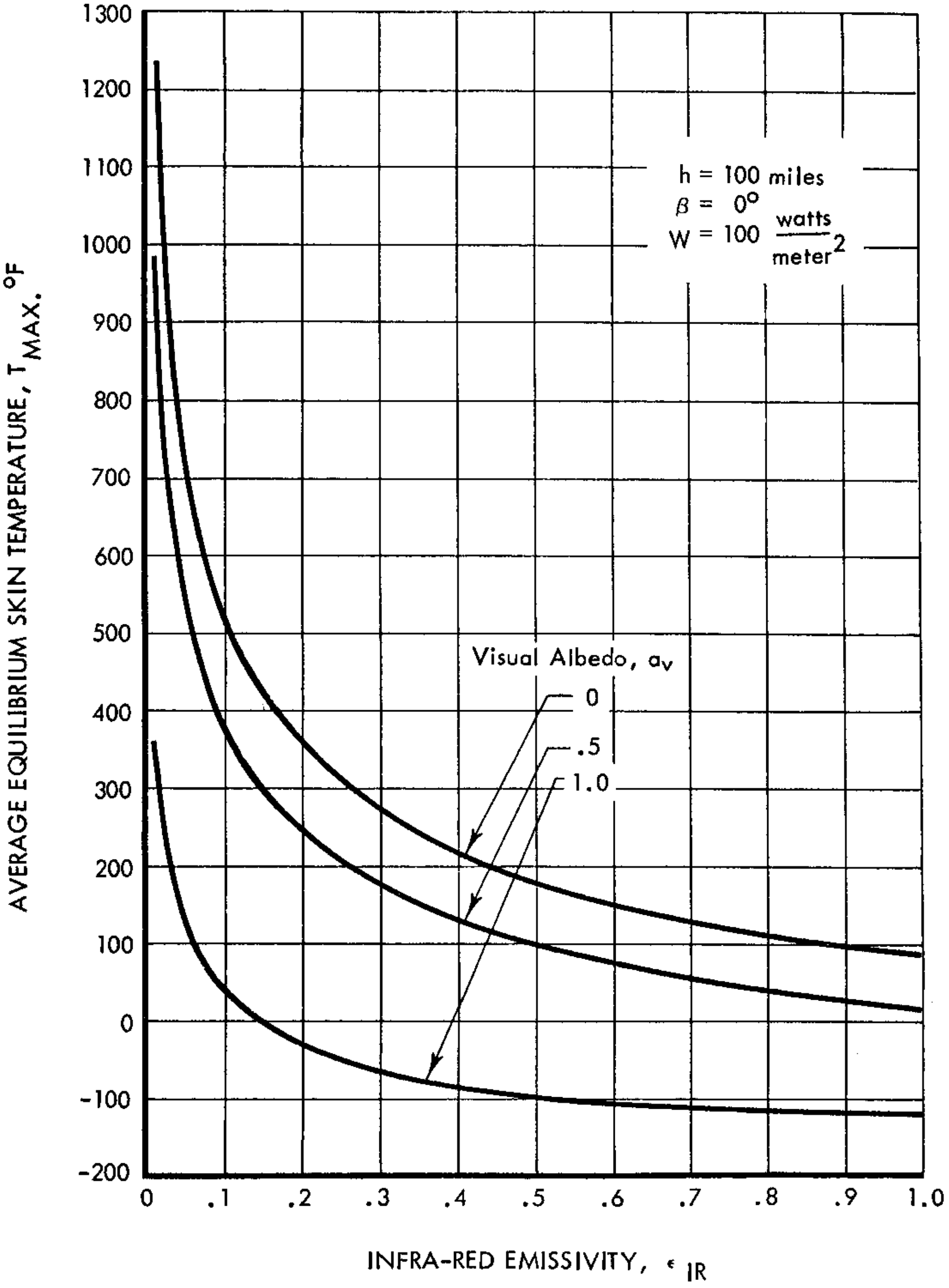


FIGURE III-12b

AVERAGE EQUILIBRIUM SKIN TEMPERATURES DURING SUNLIT PORTION OF ORBIT AS A FUNCTION OF SURFACE CHARACTERISTICS AND INTERNAL POWER LEVEL

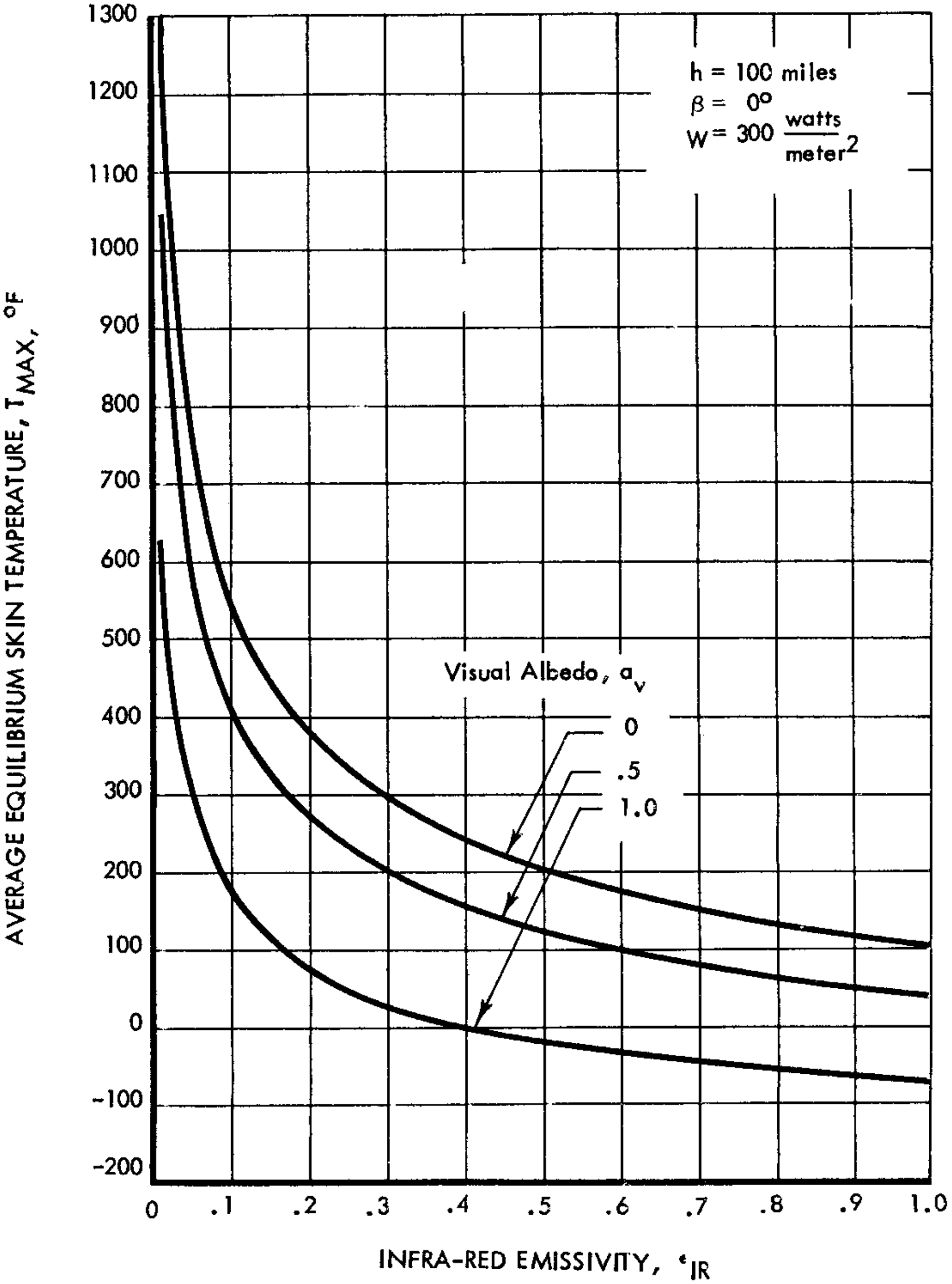


FIGURE III-12c

AVERAGE EQUILIBRIUM SKIN TEMPERATURES DURING SUNLIT PORTION OF ORBIT AS A FUNCTION OF SURFACE CHARACTERISTICS AND INTERNAL POWER LEVEL

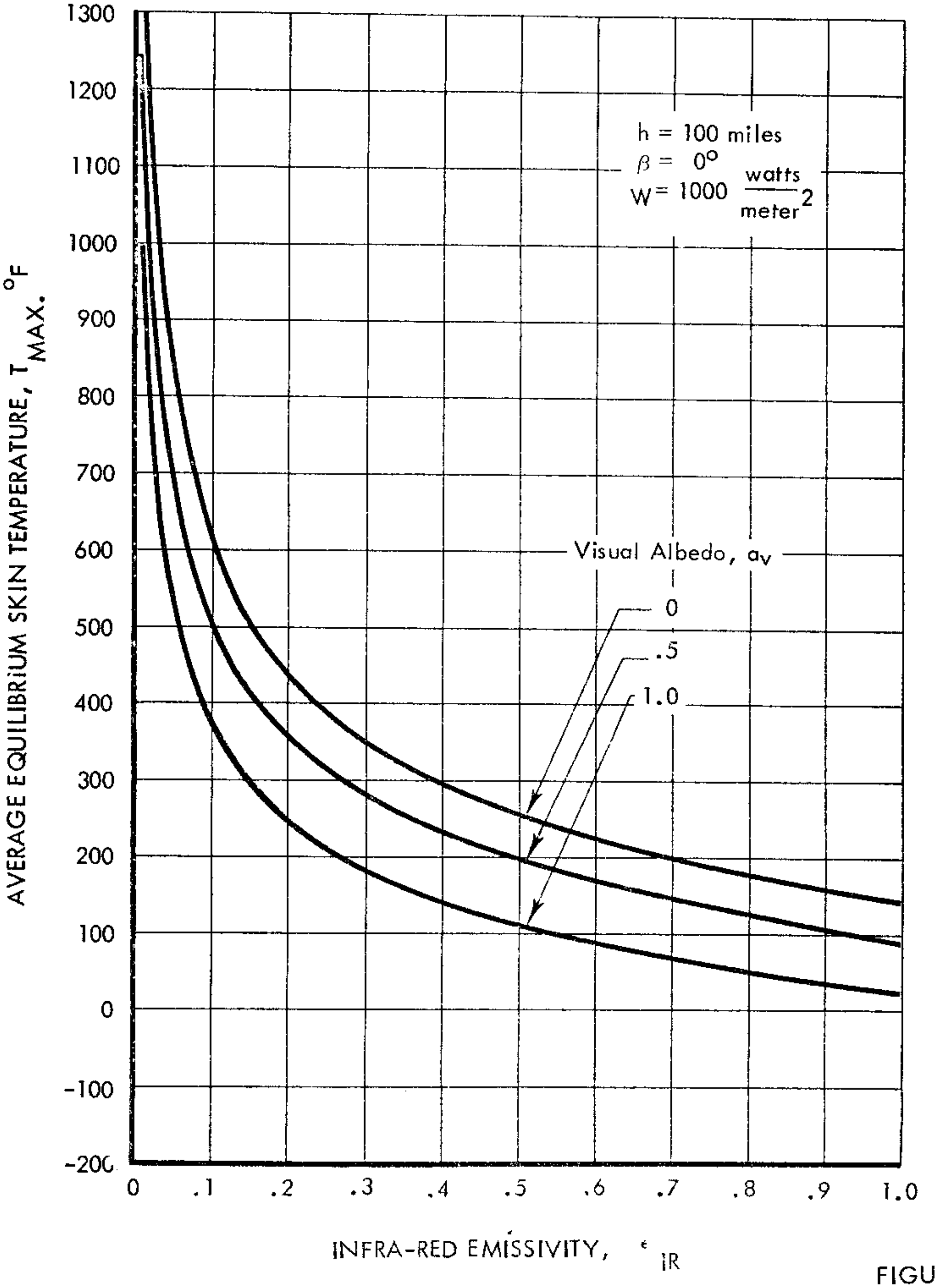


FIGURE III-12a

AVERAGE EQUILIBRIUM SKIN TEMPERATURE DURING SHADED PORTION OF ORBIT AS A FUNCTION OF SURFACE CHARACTERISTICS AND INTERNAL POWER LEVEL

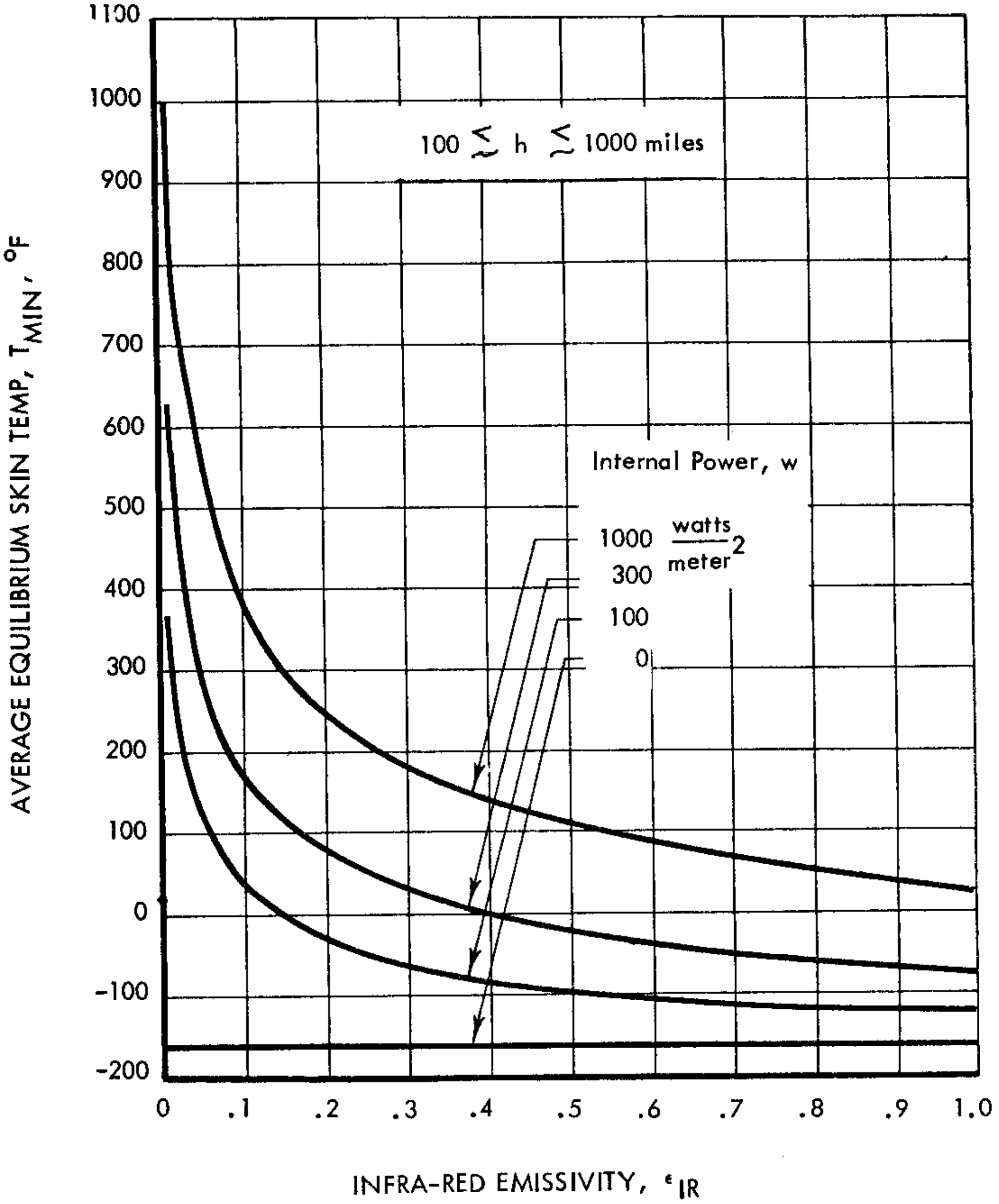


FIGURE III-13

III.7 NOMENCLATURE

a_E	Albedo of earth, ratio of reflected to incident light, ≈ 0.34
a_v	Visual albedo of the satellite
A_c	Cross-sectional area of the satellite, square meter
A_s	Surface area of satellite, square meter
B	Direct solar radiation absorbed by satellite, watts
β	Angle between the orbit plane and the sun-earth line, degrees
C	Reflected solar radiation absorbed by satellite, watts
D	Thermal radiation from earth absorbed by satellite, watts
ϵ_{IR}	Infra-red emissivity
h	Altitude of the orbit, miles
μ_T	Eclipse factor (% of time in sunlight)
I_R	Reflected solar radiation incident on satellite, watts/square meter
P	Orbital period, time to complete one revolution, hour
ψ	Angle at which the satellite goes into the earth's shadow, degrees
Q	Thermal radiation from capsule to space, watts
R_E	Radius of earth, 3959 miles
S	Solar constant, 1400 watts/square meter
σ	Stefan-Boltzmann constant, 5.67×10^{-8} watts/square meter $-{}^{\circ}K^4$
T_M	Average equilibrium skin temperature for complete orbital period
T_{MAX}	Average equilibrium skin temperature for sunlit period
T_{MIN}	Average equilibrium skin temperature for shaded period
T_s	Outer skin temperature of satellite

NOMENCLATURE (Continued)

θ	Geocentric angle along orbit, measured from noon transit, degrees
v_s	Velocity of satellite relative to the upper atmosphere, mps
W	Internal heat (power) generated, watts

APPENDIX IV

SYSTEM WEIGHT/POUND COMPRESSED OXYGEN STORED (SPHERICAL TANKS)

Consider volume of tank as V.

(1) Then weight of tank = $\rho_t At = W_T$ (spherical tank):

$t = Pr/(2sE-P) = Pr/2sE$ where $s \gg P$

Therefore

$$W_T = \frac{\rho_t Pr \cdot 4 \pi r^2}{2sE} = \frac{\rho_t P 3V}{2sE} = 1.5 \; \rho_t \frac{PV}{sE}$$

If Ti-6Al-4V is used, ultimate stress is 160,000 psi. Dividing this by safety factor of 1.5 gives 107,000 psi for sE.

Thus $W_T = 1.5 \times (280/107{,}000)PV = 39.2 \times 10^{-4}\,PV$

where P is expressed in pounds/square inch, V is expressed in cubic feet, and W_T is expressed in pounds.

(2) Gas weight (W_g) for fixed volume, V; oxygen at 70°F:

$$W_g = 32n = 32PV/ZRT = \frac{32 \cdot P \cdot 144 \cdot V}{Z \cdot 1540 \cdot 530} = 56.5 \times 10^{-4}\,(PV/Z)$$

Weight of system/weight of gas = S = 1 + (weight of tank)/(weight of gas)

$$S = 1 + \frac{39.2 \cdot 10^{-4} \cdot PV}{56.5 \cdot 10^{-4} \cdot (PV/Z)} = 1 + .695\,Z$$

If perfect gas assumed Z = 1, therefore S = 1.695 = 1.70 pounds system/pound oxygen. Thus if perfect gas law could be assumed over possible storage pressure range, the value of S would be independent of the storage pressure. At high pressures the compressibility factor Z may vary considerably from unity. It may be estimated from compressibility factor correlations based on reduced pressures (Pr) and temperature (Tr) of any gas. Thus for oxygen the critical temperature (Tc) is -119°C and the critical pressure (Pc) is 49.7 atmospheres. At 20°C:

$$Tr = T/Tc = (273 + 20)/(273 - 119) = 293/154 = 1.9$$

$$Pr = P/Pc = P/49.7$$

From Z versus Tr and Pr Plot (Ref. 52), Z = 0.95 to 1.15 for all Pr's between 0.1 to 10.0 at Tr of 1.9.

Thus for all pressures between 5 and 500 atmospheres, i.e. 70 to 7000 psia:

$$\begin{aligned} S &= 1 + 0.695\ (0.95 \text{ to } 1.15) \\ &= 1.66 \text{ to } 1.80 \text{ pounds system/pound oxygen} \end{aligned}$$

Minimum weight considerations therefore favor low pressure storage, but additional weight penalties (beyond the storage tank proper) would be incurred at high tank volumes, so some compromise would be sought. However, the system/gas weight ratio may be pegged sufficiently at this point by the above ratio, i.e.:

$$S_{O_2} = 1.66 \text{ to } 1.80 \text{ pounds system/pound oxygen.}$$

Additional Nomenclature

ρ_t = Density of material

A = Surface area of tank

V = Volume of tank

r = Radius of tank

t = Shell thickness

s = Design stress

E = Joint efficiency

P = Storage pressure

APPENDIX V

OXYGEN DERIVED FROM WASTE PRODUCTS

V.1 ELECTROLYSIS OF WATER

This requires a theoretical minimum of 1860 watt-hours/pound oxygen produced at ordinary temperatures and pressures. The maximum theoretical energy available from the most energetic chemical systems is about 3 kilowatt-hours/pound (see Table 4-6).

As no electrochemical cells have been devised for the production of power from these chemicals, some form of heat engine must be used to convert to electrical energy. Assuming overall efficiency of even 50% in the motor generator unit and 85% in the electrolysis cell, an overall efficiency of 42% (1.28 kilowatt-hour/pound chemicals) is the best that can be expected. Thus at least 1.5 pounds of chemicals would be needed to produce 1 pound of oxygen. Chemicals alone make this system heavier than a cryogenic storage system. The process can be used only where the weight/kilowatt-hour of energy required is much less than that available from chemical systems, e.g., in solar power plants operating over long durations or nuclear power plants.

V.2 REGENERATION OF OXYGEN FROM CARBON DIOXIDE BY CHEMICAL METHODS

One scheme that has been proposed (ref. 32) for the regeneration of oxygen from carbon dioxide is summarized by the following steps:

$$CO_2 + 4Na \longrightarrow 2Na_2O + C \qquad (1)$$

$$2Na_2O + 2H_2O \longrightarrow 4NaOH \qquad (2)$$

$$4NaOH \longrightarrow 4Na + 2O_2 + 2H_2 \text{ (electrolytic process)} \qquad (3)$$

$$2H_2 + 2O_2 \longrightarrow 2H_2O + O_2 \qquad (4)$$

The sum of Equations 1 to 4 is the net reaction

$$CO_2 \longrightarrow C + O_2 \qquad (5)$$

This process would remove CO_2 and produce oxygen and so is competitive, on a weight basis, with LOX at 1.15 pounds/pound O_2 and LiOH at 1.35 pounds/pound CO_2. The total system weight is 1.35 + 1.15 (32/44) = 2.2pounds/pound CO_2.

The above reaction can be eliminated by energy considerations alone. In the hydroxy fuel cell one kilowatt-hour requires one pound H_2-O_2. The minimum reversible energy required for Equation 5 is 1.12 kilowatt-hour/pound CO_2 (see Table 4-6), assuming that any energy available in Steps 1, 2, and 4 is recovered. Actually, because of the relatively small flows involved, no attempt would be made to recover energy and the energy requirements would be controlled by Step 3. This is 362 kilocalories for the reaction as written or 4.34 kilowatt-hours/pound CO_2. The 4.34 pounds H_2-O_2 required as the energy source is practically twice the weight of the system it is meant to replace. Regeneration of oxygen from carbon dioxide will probably never be worthwhile using chemical energy sources.

V.3 REGENERATION OF OXYGEN FROM CARBON DIOXIDE USING BIOLOGICAL RECYCLING PROCESSES

The production of foodstuffs and oxygen from CO_2 and waste water would be the ideal reaction. The typical reaction is:

$$12CO_2 + 11H_2O \longrightarrow \underset{\text{(sucrose)}}{C_{12}H_{22}O_{11}} + 12O_2$$

ΔF for this reaction is 1.05 kilowatt-hours/pound of reactants or products. The energy required (light) would come from chemical fuels through the conversion steps indicated below. The efficiency of each conversion has been subject to various degrees of optimism. The maximum and minimum values are indicated.

	Chemical fuel	→	electrical energy	→	active light	→	carbohydrate + oxygen
Minimum efficiency,%		20		20		10	
Energy/pound fuel, kwhr	3.0		0.6		0.12		0.012

$$\text{Pound fuel/pound reactants or products} = \frac{1.05}{0.012} = 87$$

Maximum efficiency,%		50		90		45	
Energy/pound fuel,kwhr	3.0		1.5		1.35		0.61

$$\text{Pound fuel/pound reactants or products} = \frac{1.05}{0.61} = 1.7$$

Average efficiency,%		35		55		28	
Energy/pound fuel, kwhr	3.0		1.05		0.58		0.16

$$\text{Pound fuel/pound reactants or products} = \frac{1.05}{0.16} = 6.5$$

Such a system would replace 0.47 pound sucrose + (1.15·0.53) = 0.61 pound O_2 cryogenic storage system + (1.35·0.725) = 0.98 pound LiOH (for CO_2 absorption) = 2.0 pounds total. Conventional storage systems are equivalent to the most optimistic regenerative estimates and are likely to be several times better.

APPENDIX VI

MOLECULAR SIEVES FOR CO_2 ADSORPTION

Figure VI-1 is the equipment layout for a two-column adsorption unit; adsorber A is being used for adsorption while unit B is undergoing regeneration.

The cycle time is controlled primarily by the time required for regeneration and cooling. Linde recommends a two-hour regeneration period at 400°F with the system exposed to the vacuum of space. One additional hour is used for cooling. With the simultaneous adsorption of CO_2 and HOH they recommend 3.5% loading for CO_2 and 10% loading for water vapor. Since the CO_2 to be handled is about 0.1 pound/hour, the weight of sieves required for CO_2 is $\frac{0.3}{0.035}$ = 8.6 pounds per canister. Since the HOH to be removed is also 0.1 pound/hour, the weight of sieves required for the section is $\frac{0.3}{0.1}$ = 3 pounds per canister. Thus sieves required for two canisters weigh 23 pounds. This will occupy a volume of 0.5 cubic foot (ρ sieves = 45 pounds/cubic foot. The heat required to bring the material up to 400°F is the sum of (a) the sensible heat of the sieves (C_p = 0.25 Btu/pound-°F), (b) energy required to desorb H_2O (1800 Btu/pound H_2O desorbed), and (c) energy required to desorb CO_2 (350 Btu/pound CO_2 desorbed). The total heat required for regeneration is

TWO-COLUMN ADSORPTION UNIT

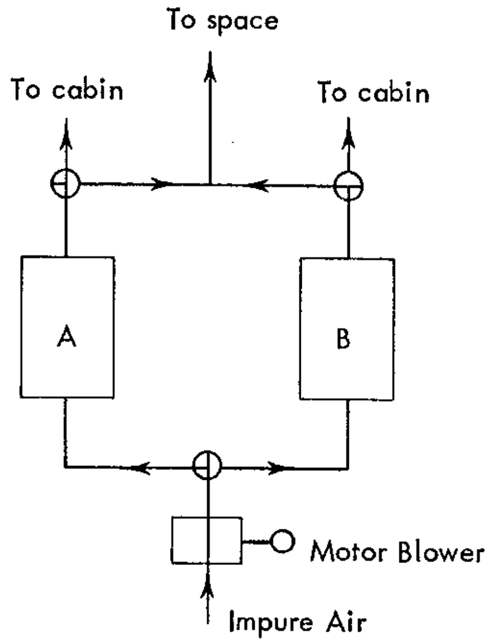


FIGURE VI-1

$$q = 0.25\,(400-70)11.6 + 1800\cdot 0.3 + 350\cdot 0.3 = 965 + 540 + 105 = 1610 \text{ Btu or}$$

an average of $\frac{1610}{3}$ = 540 Btu/hour.

If the electrical power is used for heating, this is equivalent to 0.158 watt. Assuming about 10% heat loss brings the power level to 175 watts.

At a weight penalty of 2.5 pounds chemical power system/kilowatt-hour, this is equivalent to 0.44 pound/hour or 10.5 pounds/day. This power penalty is generally greater than the combined weight of an LiOH dehumidification system, especially if one uses cryogenics for dehumidification. The regenerative power requirements are theoretically independent of the cycle time, so the only means of decreasing the power weight penalty are: (1) use solar or nuclear energy, (2) use waste heat from the power unit, or (3) remove HOH load from molecular sieves by some other means (condensation by heat exchange with cryogenics required for power or as part of thermal control unit, i.e., cooler).

Solar and nuclear energy have been excluded from this study for reasons already cited. The removal of the moisture load from the sieves seems the next best solution. Assuming that the moisture has been removed from the air stream before reaching the molecular sieves, the CO_2 adsorption system may be re-evaluted.

From the adsorption isotherms of Figure VI-2, the equilibrium adsorption is 6.4% for a partial pressure of CO_2 equal to 4 millimeters mercury. Assuming that the dynamic capacity is 80% of the equilibrium value, the CO_2 loading is 6.4 to 0.8 = 5%. For a three-hour cycle, sieves required for CO_2 removal weigh $\frac{0.3}{0.05}$ = 6 pounds/canister, or 12 pounds for two.

Energy requirements are:

a. Sensible heat = 83 Btu/pound sieves

b. CO_2 desorption energy = 350 Btu/pound CO_2 desorbed

$$g = 6 \cdot 83 + 350 \cdot 0.3 = 500 + 105 = 605 \text{ Btu/canister}$$

$$\cong 200 \text{ Btu/hour} \cong 59 \text{ watts} \cong 0.146 \text{ pound/hour of}$$

chemical power system weight or 3.5/pounds/day.

(Only 2.6 pounds LiOH/day are needed to solve the problem by chemisorption.) In addition to the weight of the sieves, one has to consider the weight of the canisters designed to withstand 14.7 pounds/square inch to keep from collapsing when exposed to vacuum, valving, piping and motor-blower unit.

These are estimated as follows:

	FOR CO_2 AND HOH REMOVAL BY SIEVES (X)	FOR CO_2 REMOVAL ONLY (Y)
Molecular sieve weight	23 Lb	12 Lb
Two Al canisters, 3/32 inch thick	8	4
Motor-blower	3	3
Three valves and solenoids	9	8
Piping, mounting, etc.	5	4
	48 Lb	31 Lb

CARBON DIOXIDE ADSORPTION

Linde Company, Molecular Sieve Type 5A

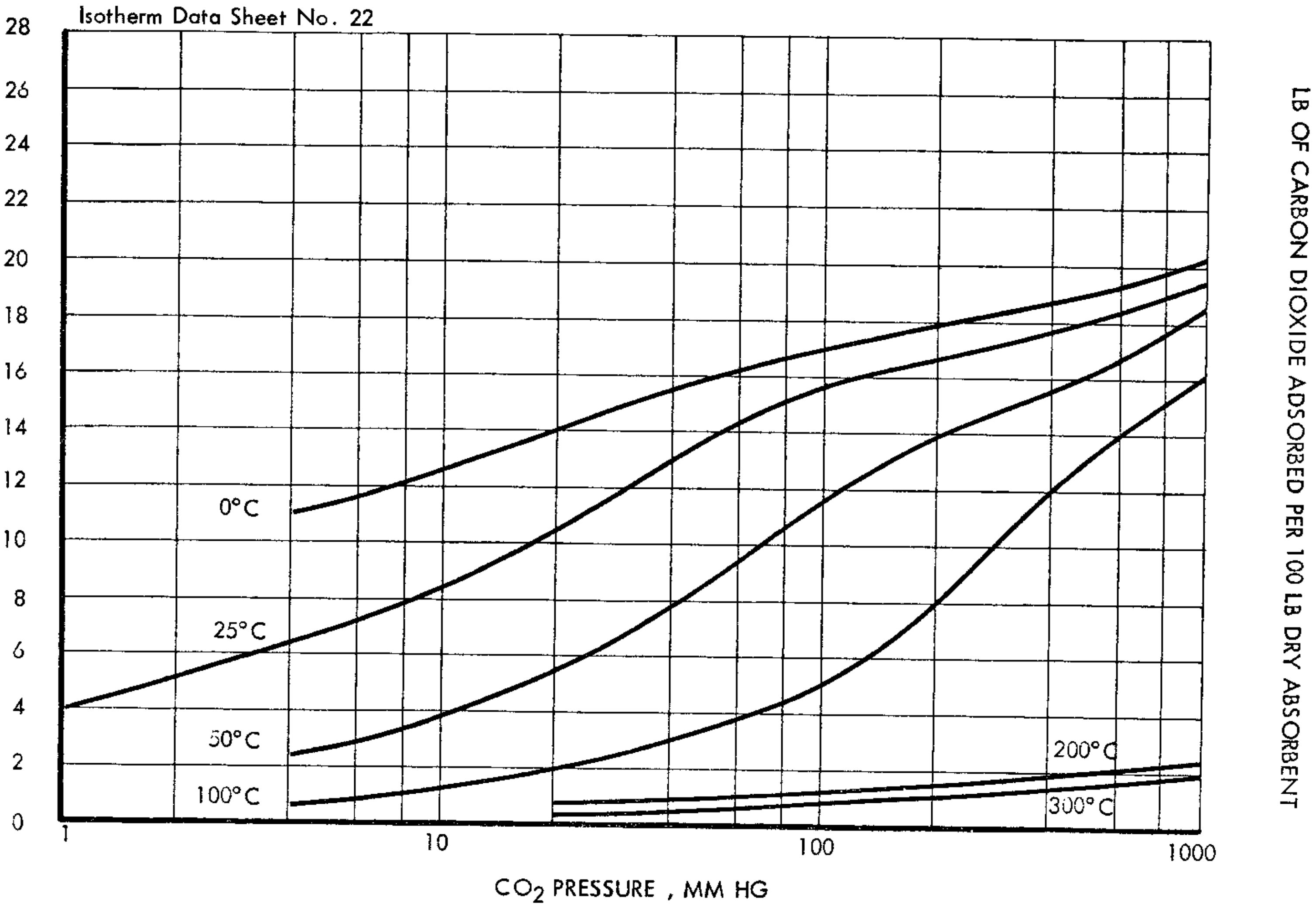


FIGURE VI-2

If regeneration heat is supplied by fuel cell thermal outputs (available at 450°to 500°F), an exchanger area and additional valving is required as shown in Figure VI-3. It is estimated that this would add 15 pounds to X (6 pounds for valves and solenoids) and 10 pounds to Y, bringing the total to 63 pounds for system X and 41 pounds for system Y. Thus using LiOH for CO_2 at the rate of 2.6 pounds/day would make the breakeven point for system Y 15 to 16 days for one man. The breakeven point for system X, i.e., simultaneous removal of CO_2 and HOH with molecular sieves, depends on the alternate methods considered. Comparing system X against the prototype design which depends on heat exchange with cryogenics to remove HOH at practically no weight penalty (i.e., less than 2 pounds) the breakeven point is 18 to 19 days, so there would be no point in using system X in this case.

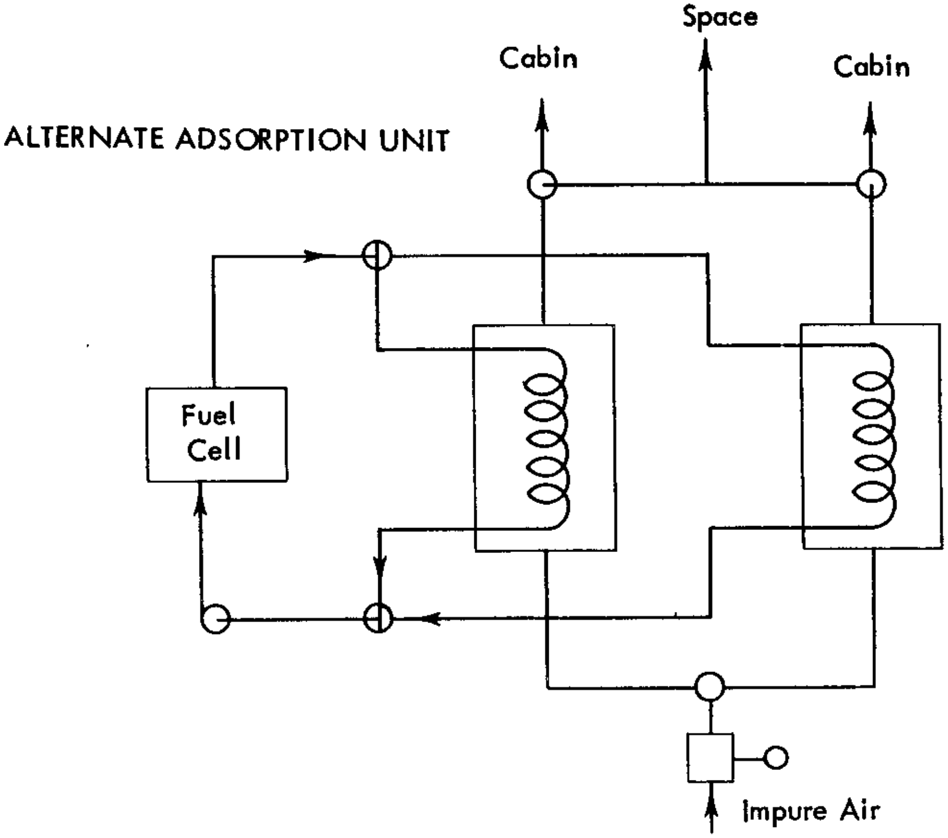


FIGURE VI-3

Other systems using molecular sieves are possible. One might use molecular sieves for CO_2 removal and silica gel for HOH removal, for silica gel requires less adsorbent for the HOH section (about half the weight required for HOH removal by molecular sieves). At the same time it increases the CO_2 capacity of molecular sieves and decreases weight for the CO_2 absorption section. Finally, adsorption of the water vapor by silica gel makes regeneration possible at a lower temperature since the main reason for the high temperature is to drive off water vapor. To capitalize on the use of both molecular sieves and silica gel, however, it would be necessary to prevent the water vapor from passing through the molecular sieves during the regeneration stage. This can be done only by using separate canisters for each adsorbent or by adding more valving to reverse the flow from the adsorption to desorption step. Since the hardware constitutes more than half the system weight using these adsorbents, the potential weight savings of a dual adsorption system cannot be ascertained without a detailed prototype design. A system using molecular sieves for CO_2 removal is so much heavier and more complicated than the relatively simple solutions selected for the mission duration involved in this study that it was not considered further in the prototype design.

APPENDIX VII

GAS EXPANSION ENGINES

The primary factor governing the system weight, including both hardware and fuel requirements, is the thermodynamic cycle. Thus for an engine of η percent efficiency, the work obtained per pound mole of gas expended is W and equals $(\eta/100)W_o$ where W_o is the work obtained for an adiabatic and isentropic expansion. For an ideal engine operating with a gas entering at T_1 and P_1 and exhausting at P_e, W_o may be derived from thermodynamic considerations and may be expressed as:

$$W_o = C_p T_1 \left[1 - (P_e/P_1)^{\frac{K-1}{K}} \right] \text{Btu/pound-mol}$$

where K is C_p/C_v, C_p is the specific heat of the gas at constant pressure, and C_v is the specific heat of the gas at constant volume.

To utilize the maximum energy of a hot gas, larger expansion ratios and high initial temperatures are necessary. Unfortunately, the initial temperatures that can be used in present engines are limited by the materials of construction rather than inherent limitations in the combustion process. Thus a diluent is necessary to keep the inlet temperature down to 2000° to 2400°R. High expansion ratios cannot be achieved across a single stage of most engines because of leakage losses or clearance problems; therefore one must resort to multiple expansions to achieve low specific fuel consumption.

Some idea of specific fuel consumption may be obtained by a thermodynamic analysis of the hydrogen-oxygen system under the following conditions: Assume that hydrogen and oxygen are available at 600°R and 1000 psia and that materials of construction limit the maximum temperature to 2400°R. Assume that the gases exhaust to 1 psia.

The specific fuel consumption using hydrogen as the diluent, single-stage burning, and several heat exchanger efficiencies between the inlet and exhaust gases is plotted as a function of engine efficiency (η) in Figure VII-1. With a much more complex system involving a three-stage burning and expansion process, as indicated in the schematic portion of Figure VII-2, improved specific fuel consumption can be achieved, as shown by the curves. The improvement in SFC resulting from heat exchangers is also significant, especially at lower engine efficiencies. One may conclude, therefore, that low SFC's are possible but not without high engine efficiencies and added complexity and weight of equipment.

Specific fuel consumption is only one factor involved in system weight. Any optimization study should also consider the weight of the power converting equipment and storage tank for fuels. These factors offer no special problems; the main uncertainty in the system weight is in the mechanical engine efficiency attainable in the power range of interest. The

THEORETICAL FUEL CONSUMPTION FOR SINGLE STAGE ENGINE

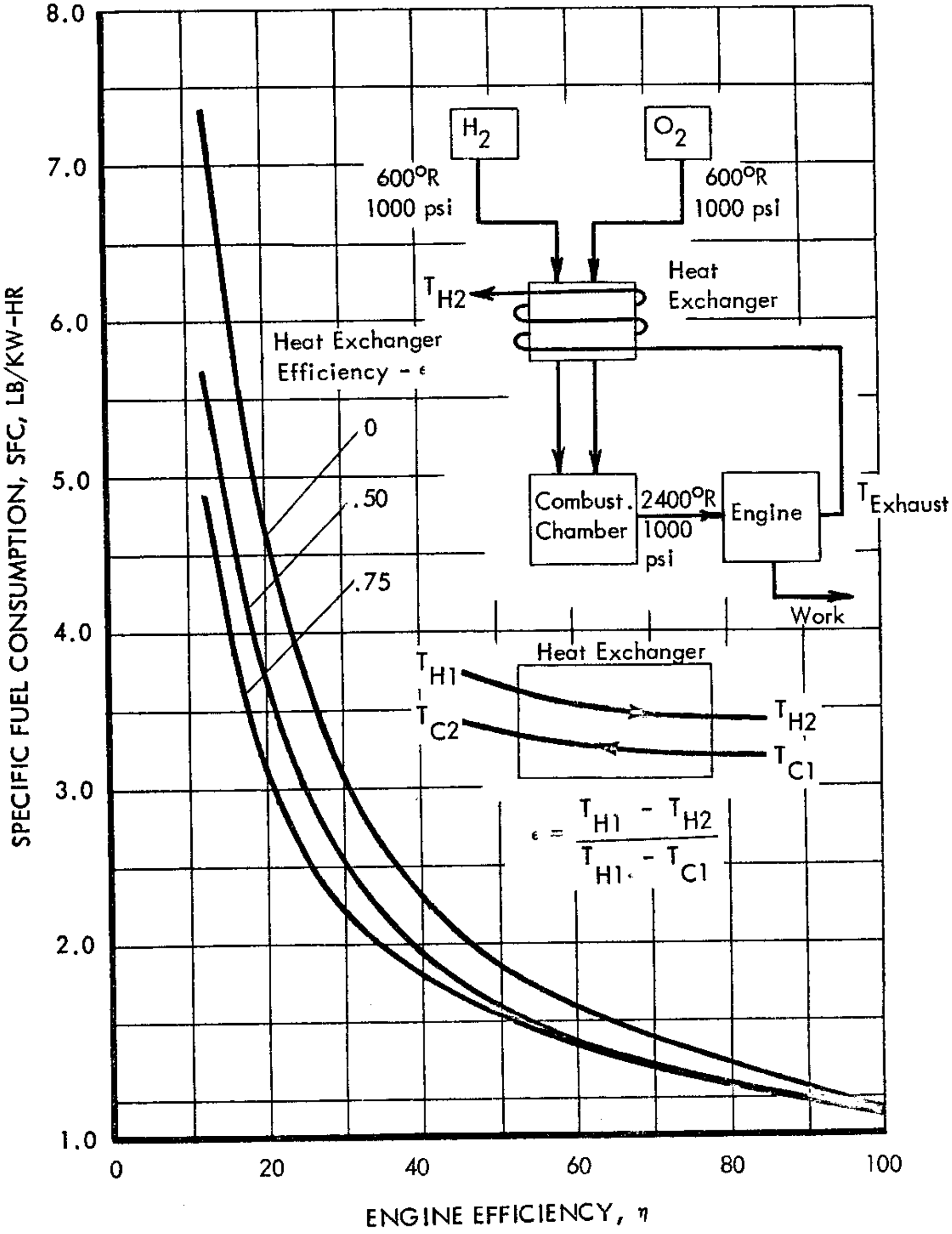


FIGURE VII-1

THEORETICAL FUEL CONSUMPTION FOR THREE STAGE ENGINE

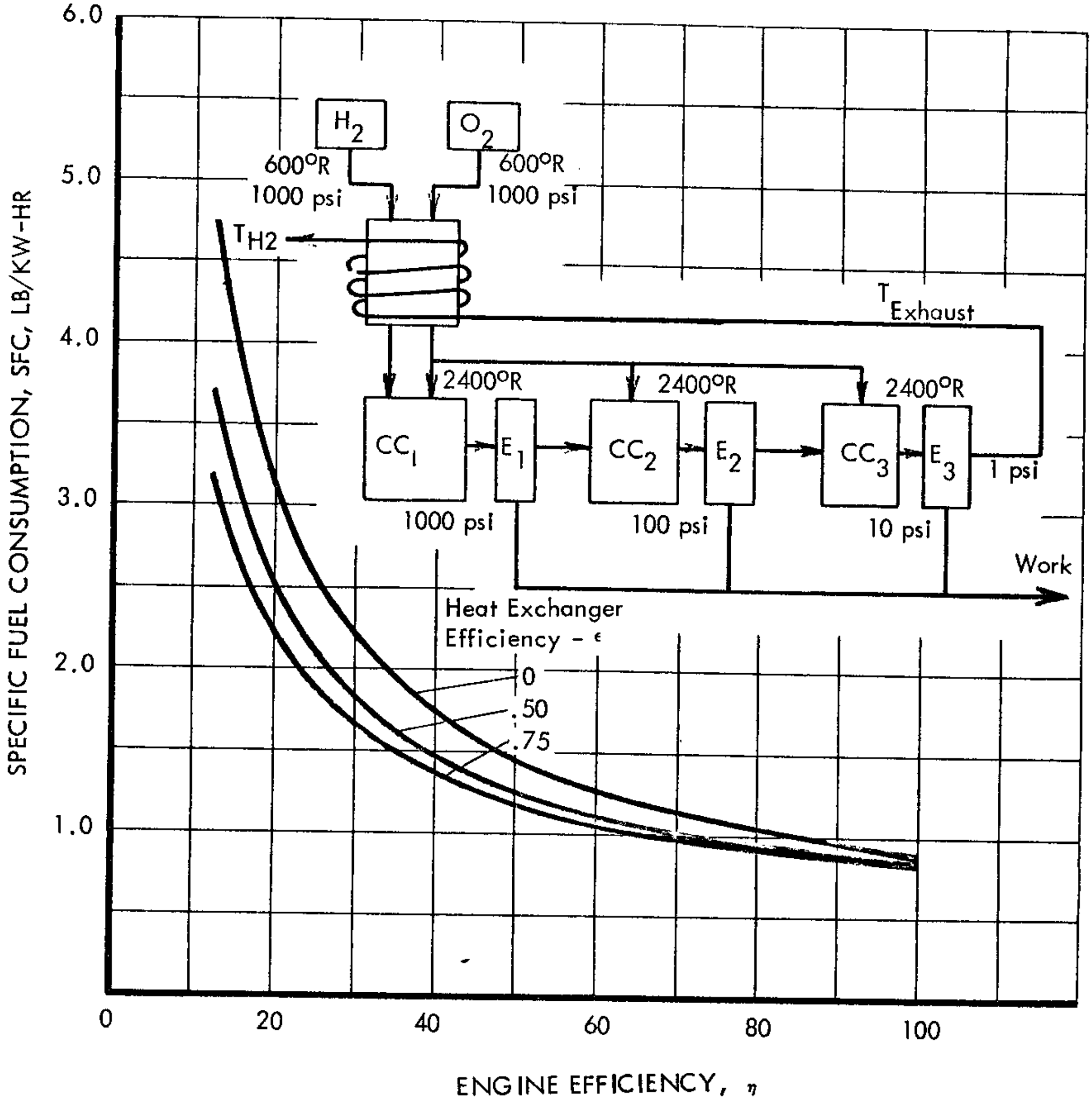


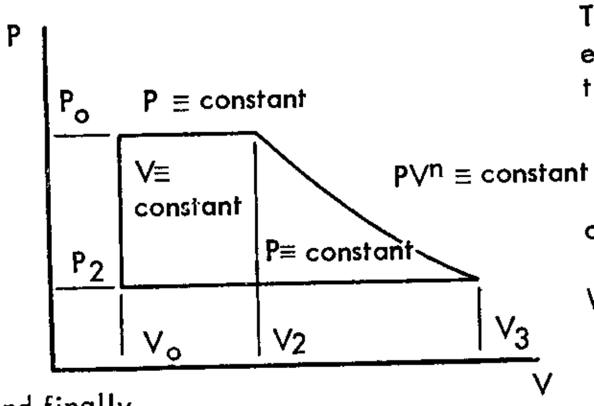
FIGURE VII-2

inefficiencies are the sum of the individual losses around the engine. Examining these losses for two general types of expansion engines, piston engines and turbines, indicates the efficiencies that may be expected. The inefficiencies are a function of the power level, but rather than attempt broad generalizations that would require an extended study, we considered efficiencies in terms of a 10-kilowatt unit. This might be considered the upper limit of the present requirements in the space capsule. A cycle pressure ratio of 500:1 with inlet pressure of 500 psia is considered compatible with the gases being stored at 800 psia. The latter pressure is used for the fuel cell and would make the final weights of the various systems easier to compare. The inlet temperature is limited to 2060°R. A marked improvement in performance can be achieved with a piston engine at high pressure levels; therefore, inlet and exit pressures of 1000 psia and 10 psia, respectively, were also analyzed for this expander.

VII.1 PISTON EXPANDERS

Losses

In addition to the friction losses inherent in a positive displacement expander, radiation losses are introduced because for proper lubrication cylinder wall temperatures are limited. The radiation loss depends upon the gas temperature and surface area of the chamber, both of which can be related mathematically to the stroke and bore. The friction losses are due primarily to the piston friction with other losses due to valves, cams, sleeves, and bearings. The friction losses depend upon the rotational speed, the stroke, the bore and the various bearing loads. The various losses do not all have the same dependence on these parameteis, so a simple empirical relation for the total friction loss is difficult.



The ideal expansion process through a piston engine is shown at the left; the power extraction is given by:

$$W = \oint P dV$$

or

$$W=(V_2-V_o)P_o-P_2(V_3-V_o)+P_oV_2^{\,n}\int_{V_2}^{V_3}\frac{dV}{V^n}$$

and finally

$$W = P_oV_3\left\{\left(\frac{V_2}{V_3}\right)-\left(\frac{V_o}{V_3}\right)-\frac{P_2}{P_o}\left[1-\left(\frac{V_o}{V_3}\right)\right]+\frac{V_2/V_3}{n-1}\left[1-\left(\frac{P_2}{P_o}\right)^{\frac{n-1}{n}}\right]\right\}$$

This is the ideal "cylinder" work. Valve losses and the acceleration of gas particles (non-equilibrium expansion), however, reduce extraction of work. The PV diagram is further modified by the radiation of energy from the gas to the cylinder walls which, for proper lubrication, must be kept at a temperature considerably lower than that of the gases.

The effect of the valves and piston acceleration on the cylinder work will be given by:

$$W_i = \eta_i W$$

(From representative engines η_i has the value 0.95.) The radiation loss is given by:

$$Q_R = \sigma \epsilon A (T_{GM}^4 - T_W^4)$$

where T_{GM} is the mean gas temperature (°R), T_W is the wall temperature (°R), and A is the chamber surface area.

$$A = 2 \pi D^2/4 + Dl$$

The radiation loss will be added to the friction loss and considered as part of the shaft load. The friction loss per piston of the engine is given empirically by the expression:

$$HP_f = K D l^2 (N/1000)^2$$

where D is the piston bore in inches, l is the stroke in inches, N is the engine speed in rpm.

These parameters have been correlated from published data of various investigators (refs. 33 through 37) and the results are presented in Figure VII-3. The references upon which the curves are based include various losses in the friction loss which are not applicable here (i.e., pumping loss, fan, etc.). From Reference 34, the portion of the friction loss as given by curves A, C, D, E, and F due to mechanical friction is approximately 50%. Application of this rule of thumb would make these data consistent with curve B which is the basis for the frictional losses calculated for the piston engine being considered. The constant K, calculated from curve B, is 4.125×10^{-3} and is assumed applicable for our engine.

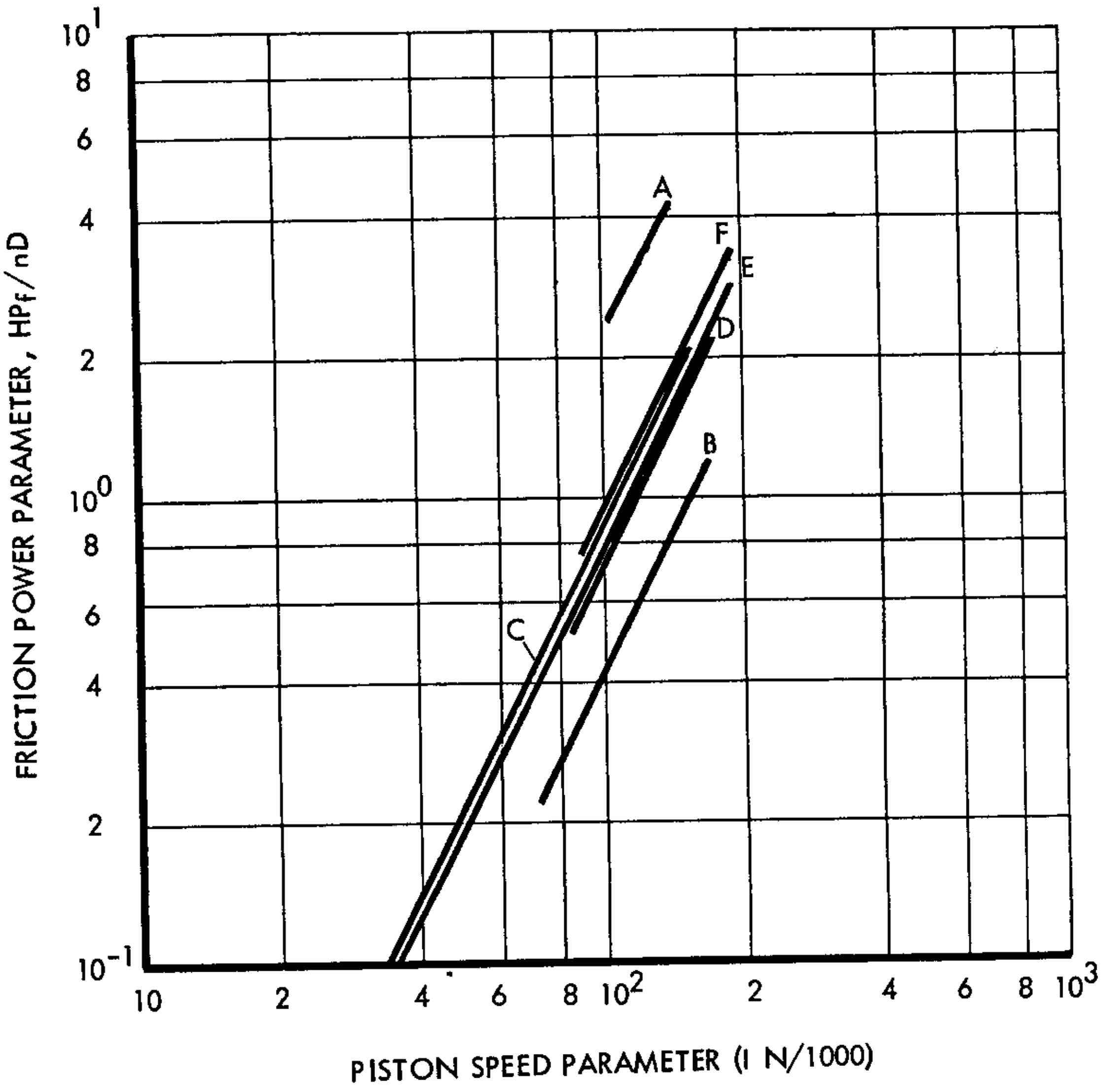
The diameter, stroke, and engine speed are also related to the volume flow of the engine by the relation:

$$Q_v = n \frac{\pi}{4} \frac{D^2 l N}{1728}$$

where n = 1 for single acting and 2 for double acting.

Optimum values of l/D may be obtained from these relations by minimizing the losses. A value of l/D equal to 0.9 results in reasonable losses in addition to yielding tolerable piston velocities. Further optimizations are possible with regard to W = PdV by varying the expansion ratio and/or the admission $(V_2-V_o)/(V_3-V_o)$; however, these are beyond the scope of this analysis. The performance as indicated is within 10% of the optimum.

POWER LOSS DUE TO FRICTION



n No. of pistons
D Piston Bore , Inches
l Stroke , Inches
N Engine speed , rpm

	n	D	l	Reference
A	12	6	7-3/8	33
B	6	3-13/16	4-3/8	34
C	8	3-3/4	3	35
D	8	3-7/16	4-5/16	36
E	8	3-1/2	3-1/4	37
F	6	3-1/2	4-1/8	36

FIGURE VII-3

Cycle and Configurations Considered for the Piston Engine

An attempt was made to utilize the piston expander for the entire expansion from 500 to 1 psia. However, the large volume flows at the exhaust conditions resulted in an excessively large expander for the final stage with prohibitive friction losses. An inlet pressure of 1000 psia resulted in a very efficient piston expander. The low volume flows which resulted produced reductions in engine bores and strokes with subsequent reductions in friction and radiation losses at lower rotational speeds. No gear box is necessary since the piston engine speed and generator speed are compatible. This, in addition to the small engine weight, helps to keep the dead weight of the system at a minimum.

Both hydrogen and water were considered as diluents. Hydrogen, having a large C_p on a per pound basis resulting in lower dilution requirements, would appear superior to water as a diluent. However, water is easily condensed and may be recirculated, effecting considerable saving in diluent weight requirements at the expense of added complexity (a space radiator) and dead weight.

The engines selected are described in Table VII-1(A and B) and are geometrically similar. The initial expansion is with a single-acting piston succeeded by a reheat phase and further expansion. The second expansion occurs with a double-acting piston. Working fluid is fed alternately to both sides of the piston, thereby reducing the required stroke and bore at a given speed with a subsequent reduction in the friction losses. Both engines are jacketed with the diluent for cooling, thereby recovering most of the radiated heat losses.

Three water-diluent systems were computed for system weights: (1) water carried on board, (2) space radiator with 1 pound/square foot of surface, and (3) space radiator with 2 pounds/square foot of surface (for meteorite protection). The results are plotted versus flight duration (Figure 5-1). Although systems utilizing water storage have high initial weights due to the space radiator, they are preferred for durations exceeding one day. This is due primarily to the weight penalty of hydrogen storage.

VII.2 TURBINES

When considering a turbine for the large expansion ratios, excessive wheel speeds and stage numbers are necessary to obtain maximum efficiencies from a turbine expander. The interstage leakages, disk friction, and pumping losses associated with small wheels at high rotative speeds prohibit their use. Utilization of a re-entry turbine while retaining the advantages of multistaging reduces the pumping and disk windage losses appreciably. However, a leakage loss (carry-over) is introduced since the wheel for this type of turbine alternately passes through arcs of high and low densities. This means that for stages following a high density pass, only a fraction of the initial weight flow is available.

TABLE VII-1

SUMMARY OF ENGINE CONFIGURATIONS

A. PISTON ENGINE

Gas: Steam with hydrogen diluent
Number of expanders: 2

	First Expander	Second Expander
Inlet Pressure	1000 Psia	100 Psia
Exit Pressure	100 Psia	10 Psia
Inlet Temperature	2060°R	2060°R
Bore	1.250 Inches	2.150 Inches
Stroke	1.125 Inches	1.930 Inches
Speed	8000 Rpm	8000 Rpm
Weight Flow	11.73 Lb/hr	14.95 Lb/hr
Piston Power	7.83 Hp	7.83 Hp
Friction Loss	0.40 Hp	1.86 Hp
Shaft Power	13.4 Hp = 10 Kw	
Fuel Flow: H_2	5.08 Lb/hr	
O_2	9.87 Lb/hr	
SFC	1.495 Lb/kw-hr	

B. PISTON ENGINE

Gas: Steam with water diluent
Number of expanders: 2

	First Expander	Second Expander
Inlet Pressure	1000 Psia	100 Psia
Exit Pressure	100 Psia	10 Psia
Inlet Temperature	2060°R	2060°R
Bore	1.353 Inches	2.200 Inches
Stroke	1.217 Inches	1.980 Inches
Speed	8000 Rpm	8000 Rpm
Weight Flow	51.4 Lb/hr	55.6 Lb/hr
Piston Power	7.76 Hp	8.37 Hp
Friction Loss	0.44 Hp	2.28 Hp
Shaft Power	1.34 Hp = 10 kw	
Fuel Flow: H_2	1.38 Lb/hr	
O_2	10.97 Lb/hr	
SFC	1.235 Lb/kw-hr	

C. TURBINE

Two-Pass Re-Entry Turbine
Gas: Steam with hydrogen diluent

	First Stage	Second Stage
Inlet Pressure	500 Psia	10 Psia
Exit Pressure	10 Psia	1 Psia
Inlet Temperature	2060°R	1783°R
Weight Flow	0.00783 Lb/sec	0.00681 Lb/sec
Power Output	7.22 Hp	6.18 Hp
Diameter (Pitch)	4.58 Inches	4.58 Inches
Blade Height	0.150 Inch	0.150 Inch
Speed	60,000 Rpm	60,000 Rpm
Fuel Flow: H_2	15.0 Lb/hr	
O_2	13.2 Lb/hr	
Power Out	10 kw	
SFC	2.82 Lb/kw-hr	

D. PISTON AND TURBINE

Gas: Steam with Hydrogen Diluent

	Piston Engine	Turbine
Inlet Pressure	500 Psia	5 Psia
Exit Pressure	5 Psia	1 Psia
Inlet Temperature	2060°R	2060°R
Bore	2.55 Inches	4.58 Inches Pitch Diameter
Stroke	2.30 Inches	0.300 Inch Blade Height
Speed	5000 Rpm	60,000 Rpm
Weight Flow	0.00329 Lb/sec	0.00472 Lb/sec
Friction Power	1.40 Hp	---
Radiation	0.67 Hp	---
Power Out	9.47 Hp	3.93 Hp
Fuel Flow: O_2	0.00165 Lb/sec	0.00143 Lb/sec
H_2	0.00164 Lb/sec	
Total Power	10 kw	
Total Fuel	17.0 Lb/hr	
SFC	1.70 Lb/kw-hr	

E. SYSTEM "DEAD" WEIGHTS

Device:	Piston	Piston		Turbine	Piston-Turbine
Diluent	H_2	H_2O		H_2	H_2
Piston Engine	8.4	9.4		--	14.8
Turbine	--	--		10.5	12.0
Gear Box	--	--		20.0	23.0
Combustors and Fuel Valves	10	10		5.0	10.0
Lube Pump	2.0	2.0		2.0	2.0
Oil and Tank	3.0	3.0		3.0	3.0
Lines	5.0	5.0		5.0	5.0
Generator	25.0	25.0		25.0	25.0
Voltage Regulator	2.5	2.5		2.5	2.5
Speed Control	3.8	3.8		3.8	3.8
H_2O Pump	--	10.0		--	--
Space Radiator and H_2O					
at 2 Lb/ft^2 of surface	--	--	294	--	--
at 1 Lb/ft^2 of surface	--	147	--	--	--
TOTAL WEIGHT	59.7	217.7	364.7	76.8	101.1

The power extraction from a stage is:

$$P = (W_o - \Sigma W_c)\,\frac{U \Delta V_\mu}{g} + W_{c_o}\,\frac{U\,W\mu}{g}$$

where P is the power, foot-pound/second

W_{c_o} is the carry-over flow from the stage, pound/second

W_o is the flow into the stage, pound/second

U is the wheel speed at the pitch diameter, feet/second

ΔV_μ is the change in the whirl component of the absolute velocity, feet/second

$W\mu_1$ is the relative whirl component at inlet to the rotor, feet/second

ΣW_c is the various leakage flows including the carry-over.

All leakages can be minimized by loading the first stage, thereby reducing the pressure differentials across the leakage areas. The carry-over leakage is given by the expression:

$$W_{co} = w_{co}\, K_B\, U\, C\, h$$

where w_{co} is the density of the carry-over, pound/cubic foot

C is the rotor blade chord, teet

h is the rotor blade height, feet

k_B is the displacement effect of the rotor blades.

The design may thus be optimized for stage loading variation, blade height, and blade speed. The aerodynamic blading efficiencies for the sizes characteristic of the designs being considered are at present close to the optimum. Performance curves for turbines of the type under consideration (Figure VII-4) have been based on the test data obtained from present hardware.

Turbine performance is seriously impaired by both leakage losses and speed limitations resulting in a high SFC (Table VII-1C). An exceptionally large expansion ratio across the first stage of the two-pass pressure-staged re-entry turbine selected, while maintaining leakages within a tolerable limit, results in gas velocities that are incompatible with high efficiencies and the wheel speed restrictions imposed. The rotational speed of

TWO-PASS RE-ENTRY TURBINE PERFORMANCE

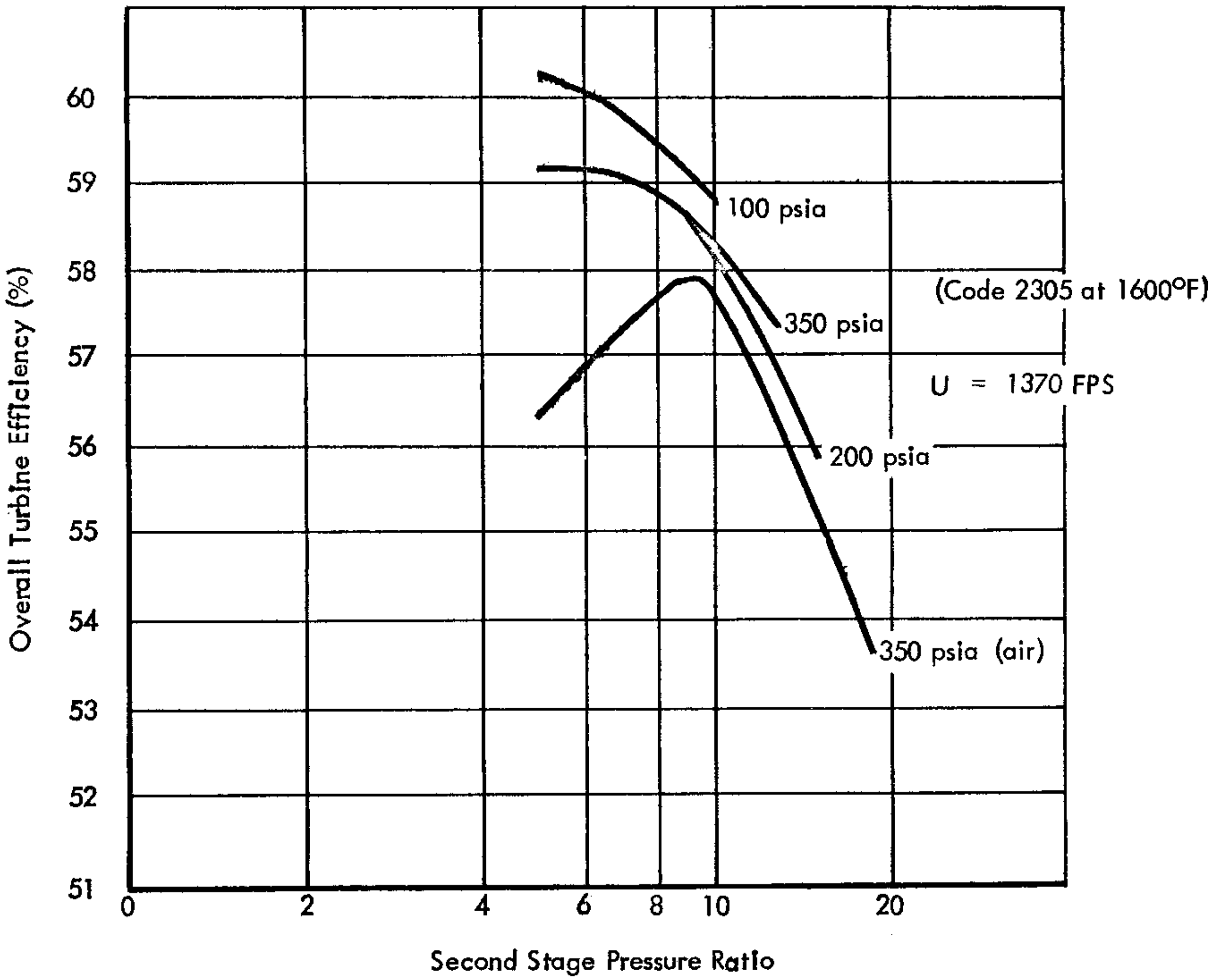


FIGURE VII-4

60,000 rpm is a practical limit requiring a gear box. From the component weights given in Table VII-1E, it is seen that the gear box makes the largest contribution to the system dead weight, aside from the generator (25 pounds).

VII.3 PISTON ENGINE AND TURBINE

Both the turbine and piston engine were seriously handicapped for operation with large expansion ratios when using hydrogen as a diluent. However, the two in combination would result in a considerable improvement in performance since it would be possible to utilize each under its most favorable operating conditions. The piston engine, whose performance is best at low volume flows, acts as the first expander whereas the turbine, as the second expander, handles the volume flows which are detrimental to piston engine performance. It is possible to optimize the pressure ratio distribution between these two expanders; however, the configuration as detailed in Table VII-1D has the maximum permissible pressure drop across the piston engine, thereby giving the turbine a more favorable loading. The performance is greatly improved compared with the turbine alone (Figure 5-1).

VII.4 SUMMARY

From theoretical calculations, specific fuel consumptions of less than 1 pound/kilowatt-hour are possible with inlet pressures of 1000 psi, pressure ratios of 1000:1, and inlet temperatures not exceeding 2400°R. Actual performance depends on engine efficiency. Unfortunately, for the relatively low power levels being considered, efficiency data on expansion engines are very meager. This is perhaps the greatest unknown in the evaluation of expansion engines power processes discussed here. Indications are that a piston engine results in the lowest fuel consumption but suffers from the high dead weight primarily due to the space radiator. The use of hydrogen as a diluent for this engine results in a very large expander in the final stage with excessive friction losses.

A two-stage, two-pass re-entry turbine, while proving to have the smallest dead weight, had the highest specific fuel consumption.

A combination formed by a piston engine to accommodate low volume flow rates at high pressures followed by a turbine to accommodate higher volume flow rates has some merit for short missions, but in long missions where fuel dominates the system weights, piston engines are preferred.

APPENDIX VIII

SPHERICAL CRYOGENIC CONTAINER WEIGHTS

In any system involving the storage of a cryogenic liquid, the inevitable transfer of heat into the liquid will ultimately manifest itself in the evaporation of the liquid or build up of pressure on the container. If the liquid is not insulated sufficiently, venting over and above the use rate will be necessary. This would result in needless loss of material. If the liquid is over-insulated, i.e., the insulation will not allow enough heat input to take care of the required evaporation rate, the system will be penalized not only by the additional weight of excessive insulation, but also by the evaporator that may be required. Logical cryogenic storage design will be determined by the amount of insulation necessary for the anticipated use rate. Use rate is only one of two major parameters necessary to evaluate insulation requirements; the other is the duration over which the fluid is to be used. The longer the duration, the greater the need is for more effective insulation for any given usage rate.

In this study the system weight, expressed as pound system/pound gas stored, has been evaluated for both hydrogen and oxygen in terms of the duration and use rate. The latter parameter has actually been expressed in terms of power level requirements since it has been assumed that the gases would be used for the hydroxy fuel cell. The system weight curves so expressed may be readily converted to pounds per hour usage rates by utilizing the assumption that 1 pound of a stoichiometric mixture of hydrogen and oxygen will produce 1035 watt-hour or that 1 kilowatt-hour is equivalent to 0.1082 pound of hydrogen or 0.8586 pound of oxygen. It is important in using the system weights calculated to keep in mind that the containers were designed for an operating pressure of 800 psi. Other assumptions and restrictions concerning the results obtained will become evident in the detailed discussion that follows.

VIII.1 DESIGN PARAMETERS AND CONDITIONS

a. Power levels considered were 0.3, 1, 5, and 10 kilowatts; durations from 1 to 20 days.

b. The operating pressure of each tank was 800 psia. Ambient conditions were assumed to be 14.7 psia pressure and 90°F maximum.

c. All tanks were assumed to be spherical.

d. Various insulation systems were considered for the above usage rates and durations. High vacuum insulation (Dewar construction) was generally sufficient for high usage rates and short durations. Either Dewar construction with a radiation shield inserted between the inner and outer shell and Dewar construction with insulating powder filling the vacuum space is sufficient for our storage systems.

VIII.2 SHELL AND SHIELD WEIGHTS

The weight of the shell or shields is equal to the product of the surface area (A), thickness (t), and material density (ρ). Thus:

$$\text{Inner shell weight} = W_1 = \rho_1 \pi d_1^2 t_1$$

$$\text{Shield weight} = W_2 = \rho_2 \pi d_2^2 t_2$$

$$\text{Outer shell weight} = W_3 = \rho_3 \pi d_3^2 t_3$$

Inner Shell Weight

The inner shell thickness is based on the design of a pressure vessel, i.e.:

$$t_1 = \frac{P_1 d_1}{2(2S_1 E_1 - P_1)}$$

Since $2S_1E_1 \gg P_1$ in this application (i.e., 214,000 $\gg$ 800), we may use

$$t_1 = \frac{P_1 d_1}{4S_1 E_1}$$

A lower limit of 1/16 inch was imposed on t_1 from fabrication considerations. The material of construction chosen for the inner shell is titanium alloy Ti-6Al-4V. The selection was based on the high strength-to-weight ratio of this alloy in comparison to other materials. It has an ultimate strength of 16,000 psi and maintains impact toughness at temperature below -300°F. $\rho = 280$ pounds/cubic/foot. The allowed stress ($S_1 E_1$) was 160,000 psi, giving a safety factor of 1.5 which is acceptable in aircraft design.

Shield Weight

The radiation shield consists of a light aluminum shell inserted between the inner and outer shell. It carries no load except its own weight but is provided with a stiffening ring around its support circumference. The thickness of the shield is assumed to vary linearly with diameter and has a value of 0.025 inch for 40-inch diameter. The stiffening ring is also made of aluminum and is 1/4 inch thick and 1 inch wide for a 40-inch diameter sphere. The weight of the ring was assumed to vary as the cube of the shield radius. The shield diameter d_2 was assumed to be $(d_1 + d_3)/2$. The density of aluminum is 166 pounds/cubic foot.

Outer Shell Weight

The thickness of the outer shell is based on its ability to resist buckling by the ambient pressure. As such, the thickness may be calculated by the following formula:

$$t_3 = \left[\frac{p_o \, d_3^2}{8M} \sqrt{3(1 - \nu^2)} \right]^{1/2}$$

where p_o is the external pressure (psi), M is the modulus of elasticity of the material (psi), and ν is Poisson's ratio.

Aluminum was chosen for the outer shell because an aluminum shell weighs 20% less than a titanium shell when using the above formula. With values of M for aluminum of 9,000,000 and $\nu = 0.36$ and $p_o = 14.7$ psi, it was found that the use of the above formula resulted in ridiculously thin shells for all except the very largest diameters. Thus a minimum shell thickness of 0.080 inch was imposed on the outer shell, this thickness being the minimum that aluminum fabricators claim they can weld. A density of 166 pounds/cubic foot was used for aluminum.

The outer shell diameter was assumed to be 1.1 times the inner shell diameter with a minimum spacing of 1 inch being imposed between the two shells to permit mounting the supports for the inner shell and shield (when used). The preceding paragraphs have established the basis for calculating the individual shell weights for any container diameter desired, with or without radiation shielding. Thermal problems associated with the containers, and the evaluation of related hardware weights remain.

VIII.3 THE THERMAL PROBLEM

At 800 psia, which is above the critical pressure for both hydrogen and oxygen, the fluid in the container is a single-phase material and no problem of phase separation in a zero-gravity environment is encountered. This homogeneous phase is desirable since it simplifies the problem of fluid transport and metering, i.e. the fluid may be "pumped" out of the tank by heating it. Thus as the temperature of the fluid is raised, the amount remaining in a tank of volume V is:

$$n = \frac{PV}{ZRT}$$

where n is the number of moles remaining in the tank, P is the tank pressure (800 psia and constant), R is the gas constant, T is the temperature of the fluid in the tank, and Z is the compressibility factor of the fluid in the tank and is known as a function of P and T for most gases.

The fraction of fluid used up may be related to the temperature as follows:

Let the original number of moles of fluid in the tank be n_o and at any other temperature, n_x.

The fraction of fluid taken out $= \frac{n_o - n_x}{n_o} = F_x = 1 - (n_x/n_o)$

But $n_o = PV/Z_oRT_o$ and $n_x = PV/Z_xRT_x$

Therefore $F_x = 1 - \frac{PV}{Z_xRT_x} \quad \frac{PV}{Z_oRT_o} = 1 - Z_oT_o/Z_xT_x$

Thus the fraction used up may be determined at any temperature T_x by evaluating Z_o at 800 psia and T_o and Z_x at 800 psia and T_x. This has been done with both hydrogen and oxygen using available PV data (ref. 39) for these gases. The results are plotted in Figures VIII-1 and VIII-2. No data were available in the portions of the curves indicated by dashed lines.

The heat required to expel n moles of fluid from the container will vary depending on the amount of fluid in the tank and the enthalpy of the fluid over the temperature range indicated by ΔT. Enthalpy plots versus temperature for both hydrogen and oxygen are given in Figures VIII-3 and VIII-4.

The heat required to expel constant increments of fluid by raising the temperature may not be determined. (The heat content of the tank is not considered as it is generally insignificant in comparison to the heat content of the fluid.)

Consider the expulsion of hydrogen in increments of $0.1n_o$. The temperature must be raised from 20°K to 29°K (see Figure VIII-1). The corresponding enthalpies are 80 and 100 calories/gram. The heat required, ΔQ_1 (Btu/pound) for the expulsion of the first $0.1n_o$ equals:

$$\frac{n_o + 0.9n_o}{2} \; M(H_{29} - H_{20}) \; 1.8$$

$$= 0.95n_oM(100 - 80)1.8$$

$$= 34.2 \; n_oM$$

where n_o is the original moles contained, M is the molecular weight of the fluid and H is the enthalpy, calories/gram.

TEMPERATURE OF INNER CONTAINER REQUIRED TO MAINTAIN PRESSURE AT 800 PSIA DURING REMOVAL OF HYDROGEN AT A CONSTANT RATE AS A FUNCTION OF INITIAL HYDROGEN USED

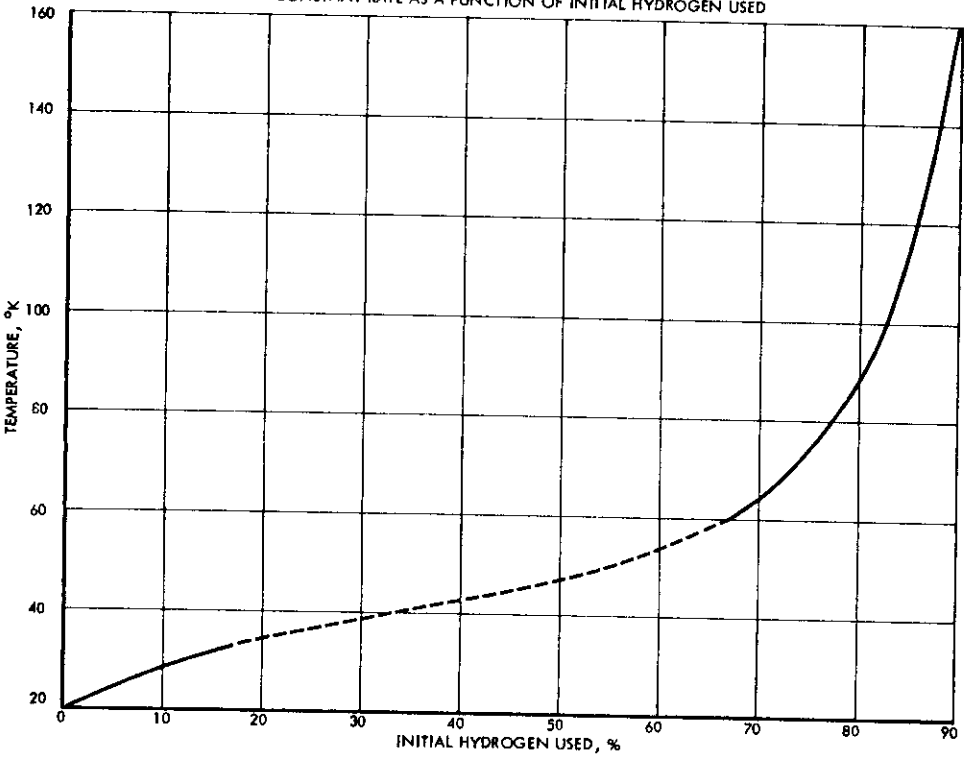


FIGURE VIII-1

TEMPERATURE OF INNER CONTAINER REQUIRED TO MAINTAIN PRESSURE AT 800 PSIA DURING REMOVAL OF OXYGEN AT A CONSTANT RATE AS A FUNCTION OF INITIAL OXYGEN

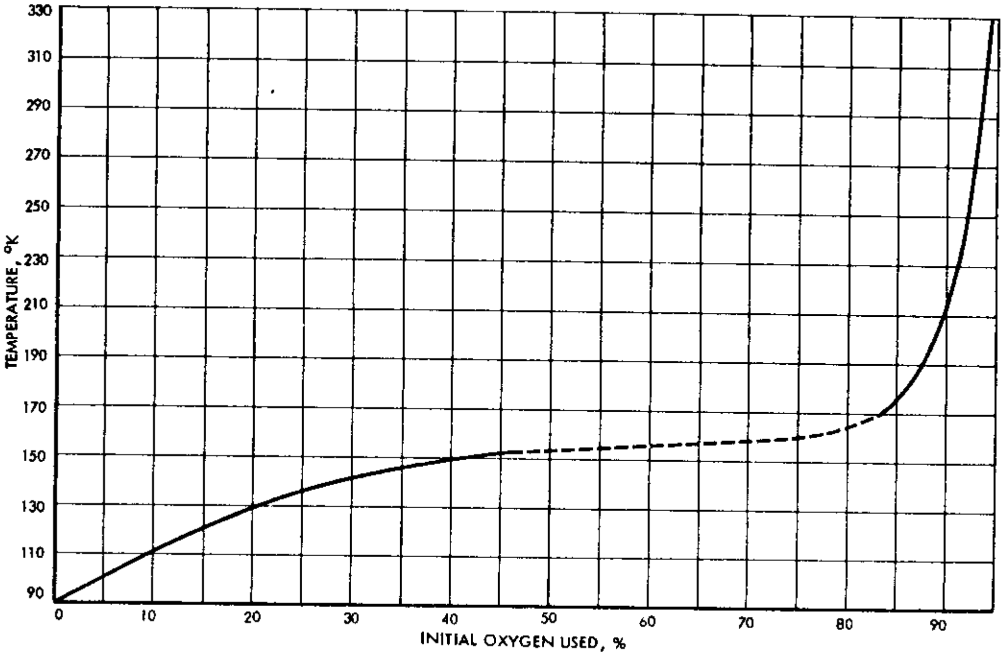


FIGURE VIII-2

ENTHALPHY AS A FUNCTION OF TEMPERATURE FOR HYDROGEN AT 800 PSIA (REF. 53)

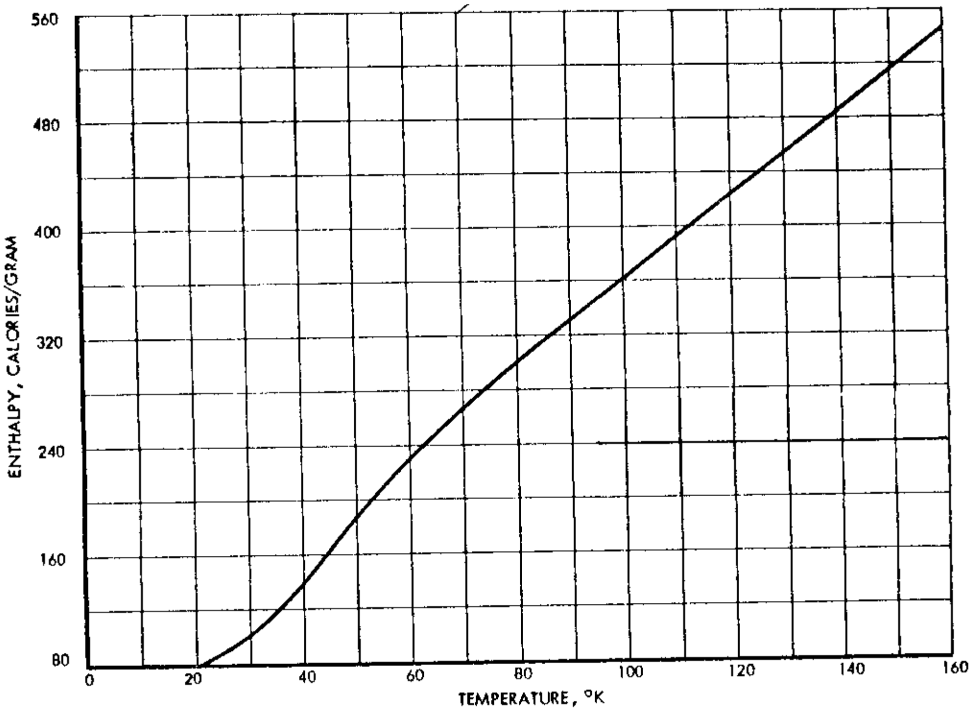


FIGURE VIII-3

ENTHALPY AS A FUNCTION OF TEMPERATURE FOR OXYGEN AT 800 PSIA

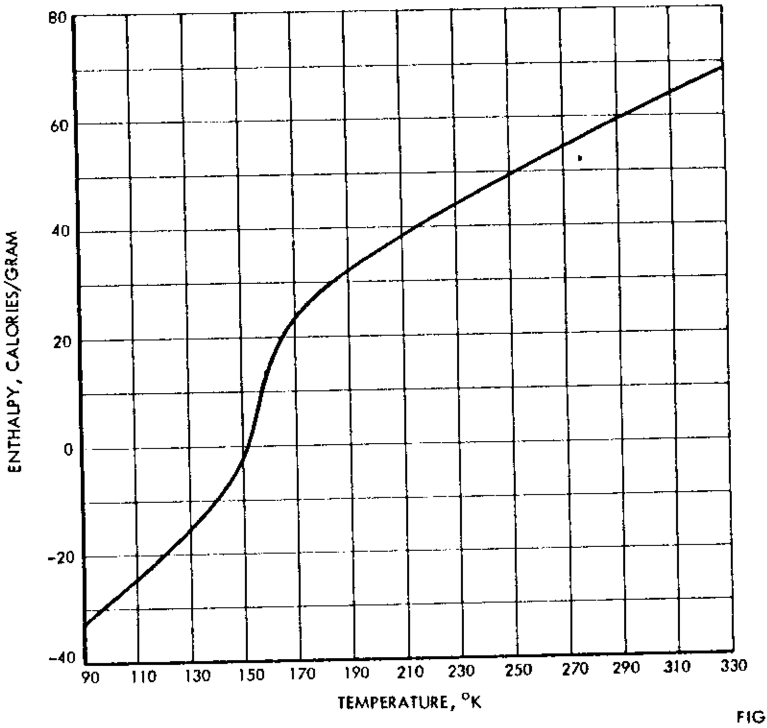


FIGURE VIII-4

For the second tenth increment expelled $\Delta Q_2 = 0.85n_oM(H_{34.5} - H_{29})$

For the third tenth increment expelled $\Delta Q_3 = 0.75n_oM(H_{39} - H_{34.5})$, etc.

The heat required per pound of fluid expelled equals:

$$\Delta Q_1' = \Delta Q_1/0.1n_oM = 9.5(H_{29}-H_{20})1.8$$

$$\Delta Q_2' = Q_2/0.1n_oM = 8.5(H_{34.5} - H_{29})1.8$$

$$\Delta Q_3' = Q_3/0.1n_oM = 7.5(H_{39} - H_{34.5})1.8$$

It becomes evident, therefore, that $\Delta Q'$, the amount of heat required per pound of fluid expelled, will depend on the temperature level in the container, and the heat required per hour will be the product of $\Delta Q'$ and the desired expulsion rate (M pound/hour). To avoid fluid losses at any time, the allowable heat leakage into the container must not exceed the minimum heat required to expel the fluid. Since for a given power level M may be considered constant, a minimum $\Delta Q'$ must be selected. This may be calculated for either hydrogen or oxygen.

Considering H_2 for example:

$Q_{Required} = M\Delta Q'$ where $M = 0.1082\ P^*$ Btu/hour when P^* is rated power in kilowatts.

Therefore $Q_{Required} = 0.1082P^*\Delta Q'$

$$\frac{Q_{Required}}{P^*} = 0.1082\,\Delta Q'$$

$$\left(\frac{Q_{Required}}{P^*}\right)_{MIN} = 0.22 \text{ Btu/kw from Figure VIII-5}$$

$\therefore$ MIN $Q_{Required} = 0.22$ Btu/hr.

From here on, the problem is the evaluation of heat leakage into the system according to conventional methods.

Evaluation of Heat Leakage Into System

(1) High Vacuum

For simple Dewar construction, i.e. high vacuum insulation, if the pressure of gas between two concentric shells is maintained at 10^{-6} millimeters mercury or less; the heat leakage is determined solely by radiation across the evacuated space.

HEAT INPUT TO HYDROGEN SYSTEM REQUIRED TO MAINTAIN A PRESSURE OF 800 PSIA DURING REMOVAL OF HYDROGEN AT A CONSTANT RATE AS FUNCTION OF PERCENT OF CONTENTS USED. HYDROGEN IS INITIALLY STORED AS A LIQUID

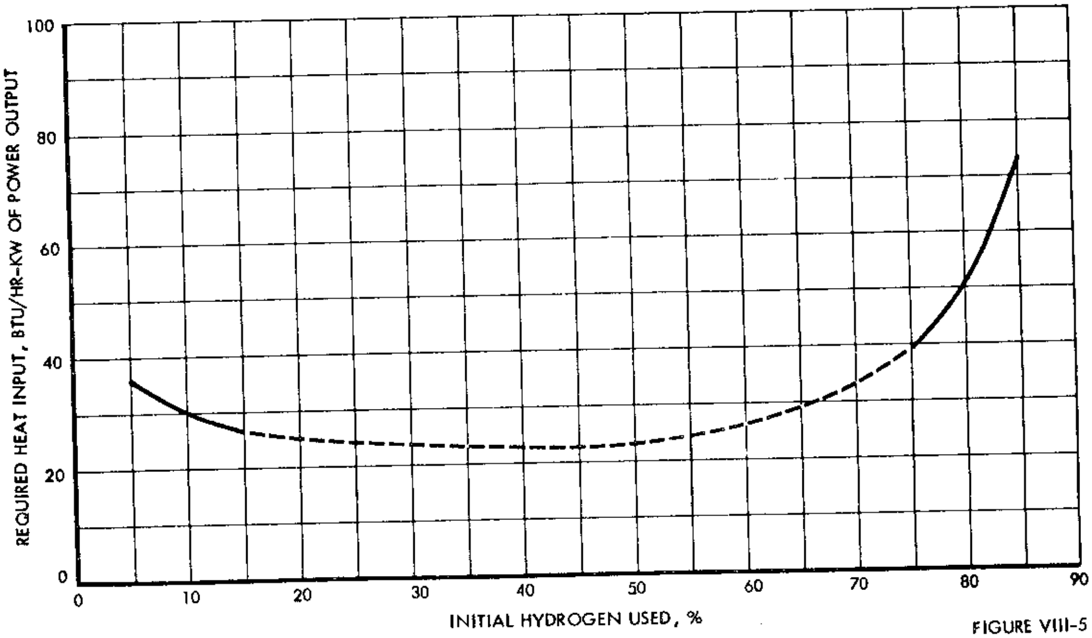


FIGURE VIII-5

HEAT INPUT TO OXYGEN SYSTEM REQUIRED TO MAINTAIN A PRESSURE OF 800 PSIA DURING REMOVAL OF OXYGEN AT A CONSTANT RATE AS FUNCTION OF PERCENT OF CONTENTS USED. OXYGEN IS INITIALLY STORED AS A LIQUID.

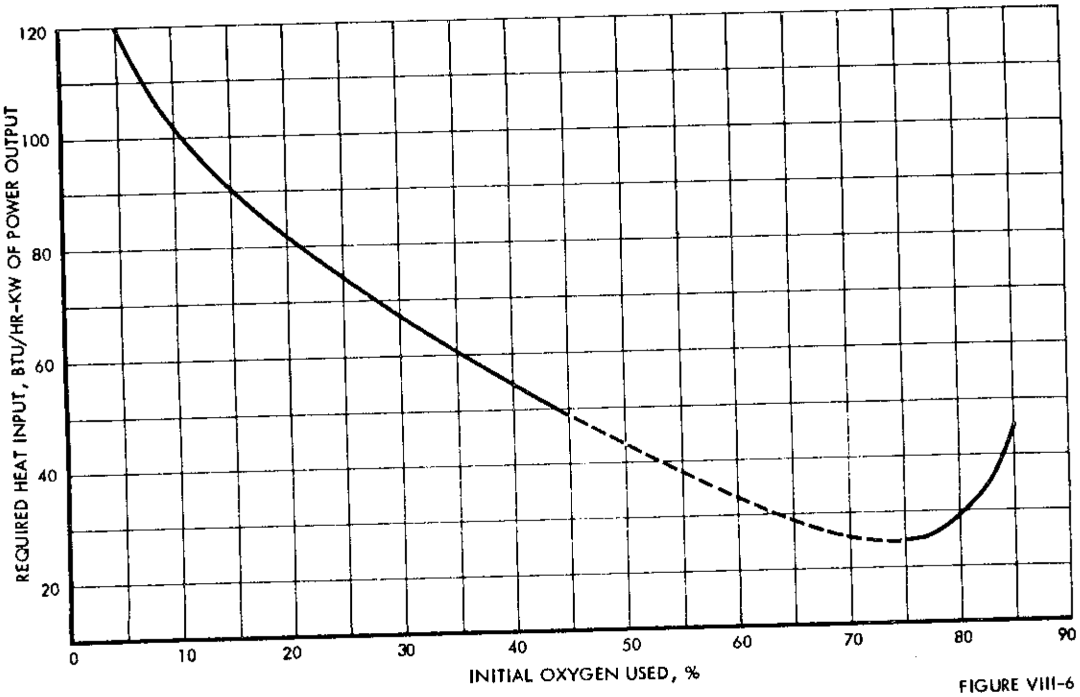


FIGURE VIII-6

The relation is:

$$Q_R = \frac{\sigma A_1 (T_2^4 - T_1^4)}{\frac{1}{\epsilon_1} + \frac{A_2}{A_1}(\frac{1}{\epsilon_2} - 1)} \qquad (A)$$

where Q_R is the heat transferred by radiation, Btu/hour

σ is 0,713 x 10^{-8} Btu/hr-ft^2-$^\circ R^4$

A is surface area, square foot

T is the absolute temperature, $^\circ$R

ϵ is the emissivity

Subscripts 1 and 2 refer to the inner and outer shells respectively.

Emissivities of all reflecting surfaces in the Dewar were assumed to be 0.03. These values may be attained with careful preparation of such surfaces. As already mentioned, the ratio between the outer and inner sphere diameters = 1.1. The outer temperature was assumed never to exceed 90°F or 550°R. T_1 would be the fluid temperature which would vary, starting at 20°K (36°R) and eventually reaching temperatures of 140° to 150°K (252° to 270°R). In either case, if it is remembered that the rate varies as T^4, it becomes evident that for practical purposes the outer temperature controls so T_1 was assumed for the first condition 36°R and left constant throughout the calculations.

If the power level (P) = 5 kilowatts, Q_R must not exceed $22 \cdot 5 = 110$ Btu/hour for hydrogen. Equation A may then be used to find the maximum size container that can be used. The volume, weight, and duration may be determined by using 4.4 pounds/cubic foot as the density for cryogenic hydrogen at 20°K and 800 psia. The duration thus calculated is represented by the circle on the system weight/pound versus duration plot (Figures VIII-7,-8, and-9. In this case the duration for a single Dewar container would be limited to 8 days at 5-kilowatt power level. For greater durations and for lower power levels additional insulation would be required. The most obvious improvement over the Dewar would be the radiation shield. System weights for oxygen are given in Figure VIII-10.

(2) High Vacuum Plus Radiation Shield

The insertion of the light weight aluminum radiation shield into the evacuated space between the two concentric spheres reduces the radiation losses. If all surface emissivities are assumed to be the same, it may be theoretically shown that the radiation losses with the shield are only 50% of those obtained without the shield. This results in a 280% improvement in allowable duration. Further improvement can be made by insertion of more shields or by the use of powder, the particles serving as multiple shields, in the vacuum space.

SPECIFIC WEIGHT OF HYDROGEN SYSTEM AS A FUNCTION OF POWER LEVEL (HYDROXY CELL ASSUMED) AND DURATION OF OPERATION. POWER LEVEL = 0.3 KW AND 1 KW.

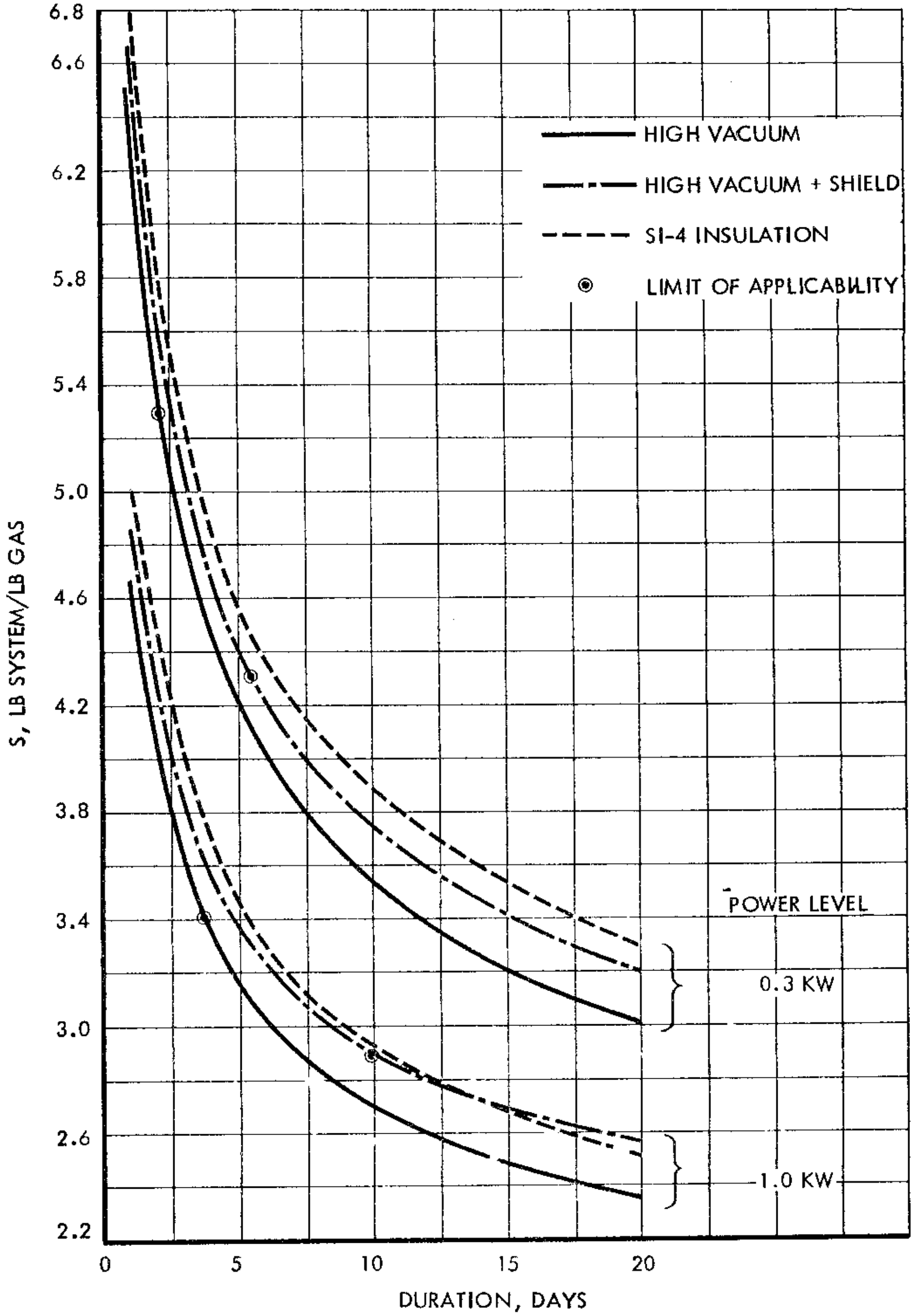


FIGURE VIII-7

SPECIFIC WEIGHT OF HYDROGEN SYSTEM AS A FUNCTION OF POWER LEVEL (HYDROXY CELL ASSUMED) AND DURATION OF OPERATION. POWER LEVEL = 5 KW

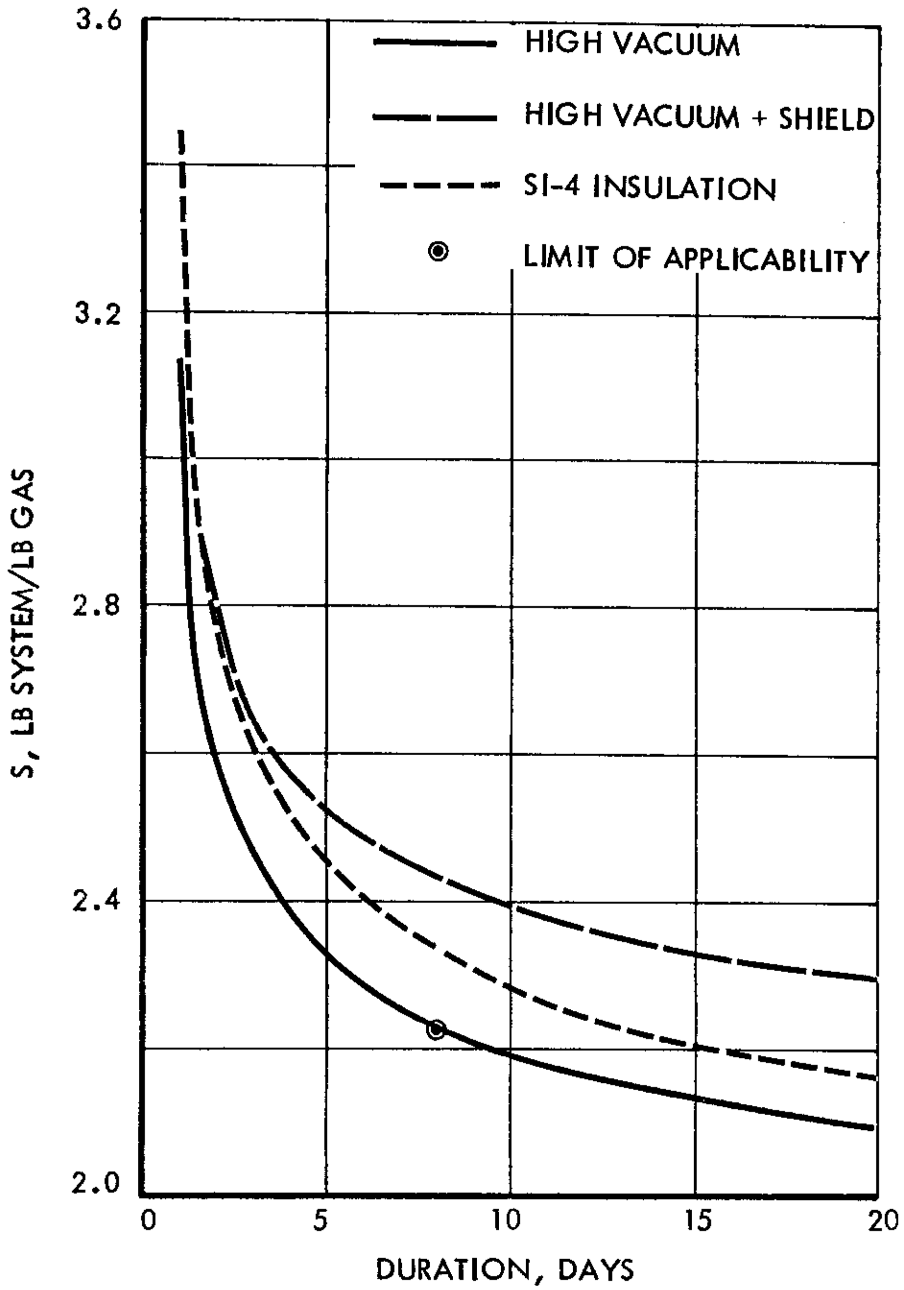


FIGURE VIII-8

SPECIFIC WEIGHT OF HYDROGEN SYSTEM AS A FUNCTION OF POWER LEVEL (HYDROXY CELL ASSUMED) AND DURATION OF OPERATION. POWER LEVEL = 10 KW

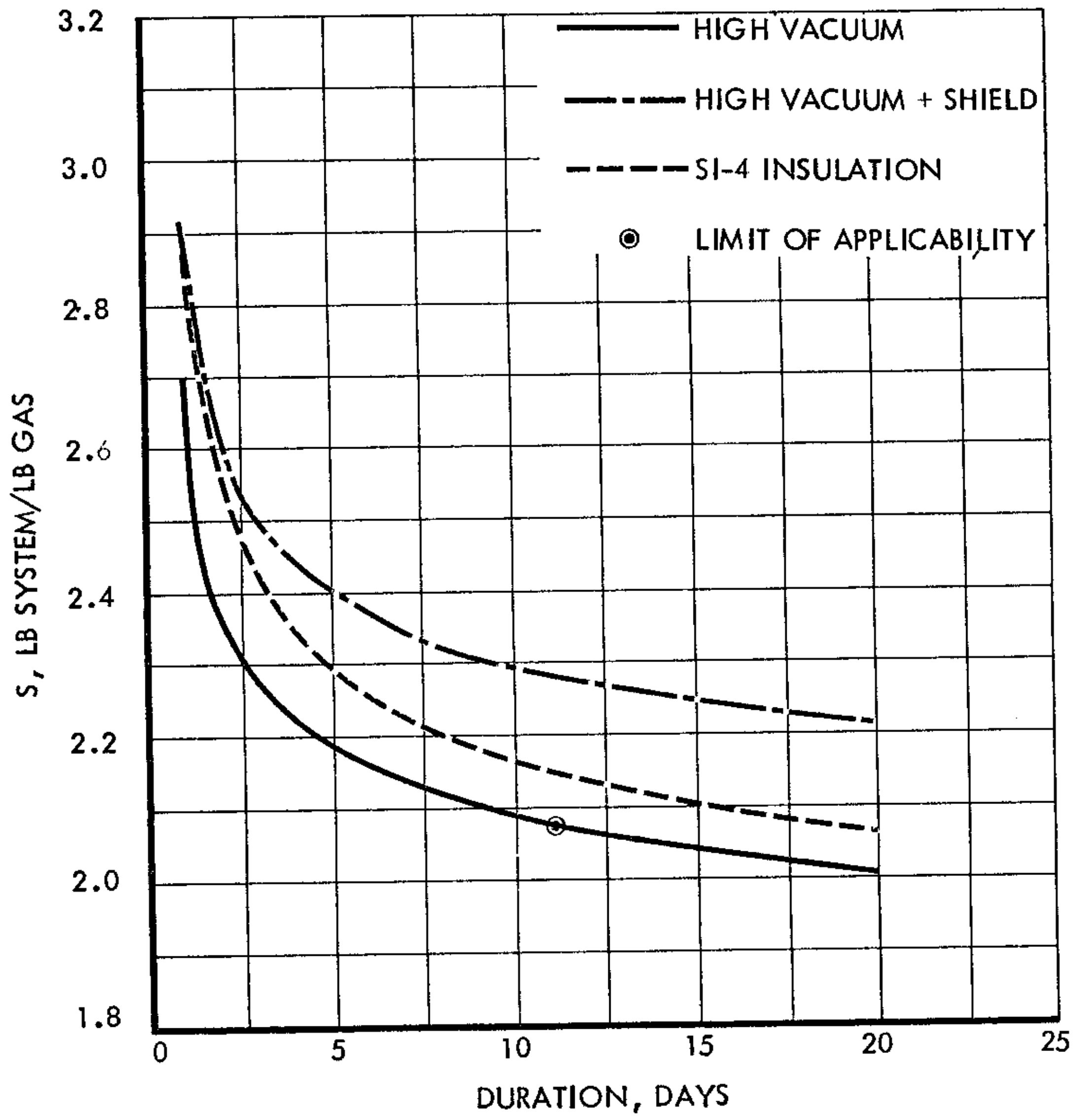


FIGURE VIII-9

SPECIFIC WEIGHT OF OXYGEN SYSTEM AS A FUNCTION OF POWER LEVEL (HYDROXY CELL ASSUMED) AND DURATION OF OPERATION

POWER LEVEL = 0.3, 1, 5, AND 10 KW

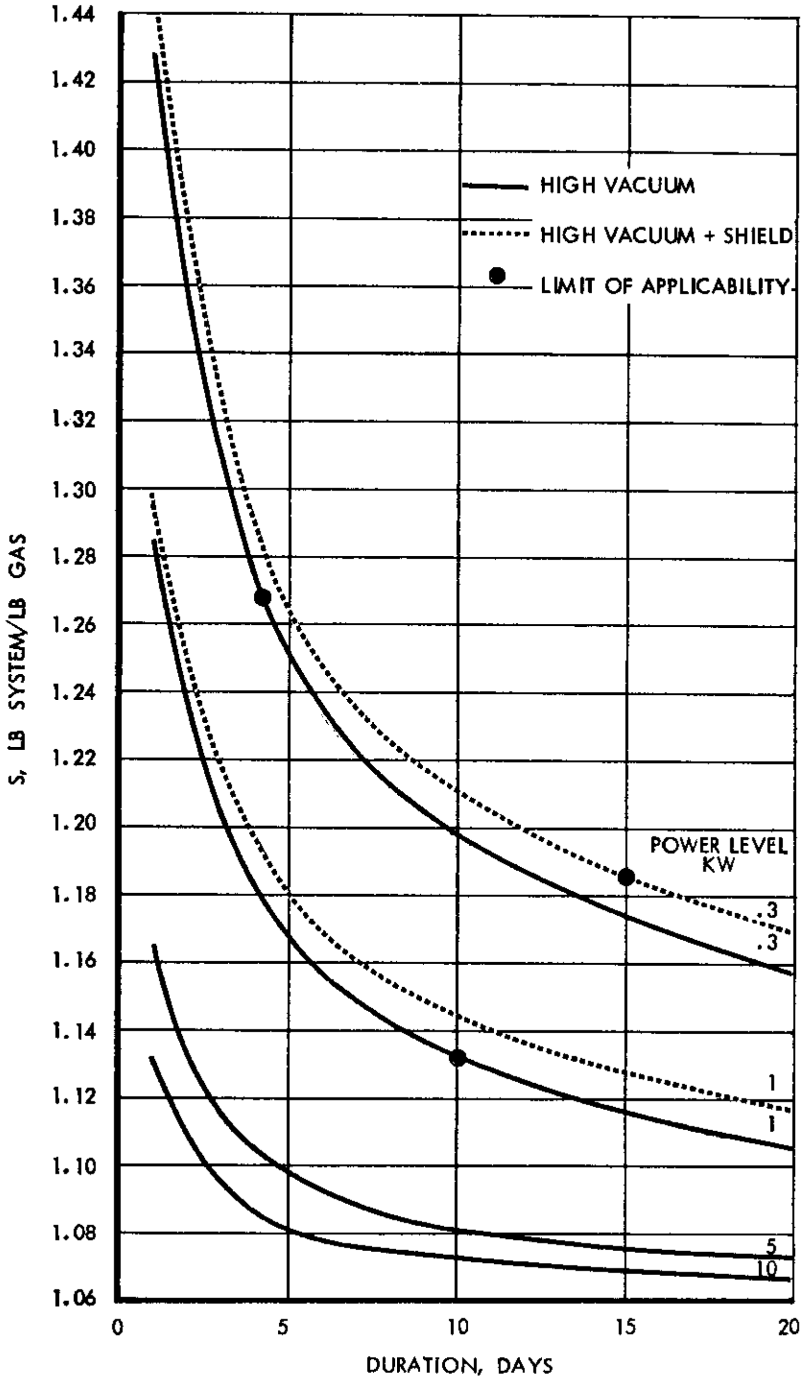


FIGURE VIII-10

(3) High Vacuum Plus Powder or Multiple Shields

When the vacuum space is filled with powder or multiple shields, the radiation losses are reduced to practically zero by the large number of surfaces available and the heat transfer mechanism is primarily by conduction across the powder bed. Thus for such materials between concentric spheres the following equation is used:

$$Q_c = (k/L)A(T_2-T_1) = 4\,\frac{\pi K \left(\frac{r_1+r_2}{2}\right)^2}{r_2 - r_1}\,(T_2-T_1) \qquad \text{(B)}$$

where Q_c is the heat conducted, Btu/hour
K is the thermal conductance of the powder, Btu/hr-ft-°R
r is the radius of the shell
and the remaining symbols are identified under Equation A.

The thickness of insulation considered was on the basis of the 1.1 ratio between the diameters with a lower limit of 1 inch.

The insulation used was the recently publicized "super" insulation developed by the Linde Company (ref. 42). The material consists of 40 to 80 layers per inch of submicron glass-fiber paper and aluminum foil insulated in the vacuum space, which must be maintained under 1-micron mercury pressure or less. This insulation which Linde designates as SI-4 has a density of 4.7 pounds/cubic foot and a thermal conductance of 0.025×10^{-3} Btu/hr-ft-°F between 80°F and -297°F if used under the above conditions. This material proved adequate for even the lowest power levels and longest durations considered.

VIII.4 AUXILIARY EQUIPMENT AND HARDWARE WEIGHT

The remaining system weights, which include support cables, piping, valves, heaters, temperature and pressure controllers, and regulators, generally represent a small fraction of container weight. We found it convenient, therefore, to use the values reported by DeHann and Piccone (ref. 43) in a detailed system study of the general problem. These results may be summarized as follows:

	Hydrogen Storage			Oxygen Storage		
	0.1 Kw	1 Kw	10 Kw	0.1 Kw	1Kw	10Kw
Total Hardware Weight, Lb, Exclusive of Shells, Shield or Super-Insulation	7.8	8.4	11.5	7.6	7.8	93

APPENDIX IX

HYDROXY FUEL CELL SYSTEM ANALYSIS

Weight of the generator is based on average values obtained for Class I, II and III generator weights described by Alexander et al. (Ref. 25, Table VIII).

Summary of Data from TR 57-605 for Generator Analysis

	Class I	Class II	Class III	
No. of cells	41	28	35	
Weight of electrodes, Lb	7.5	5.3	5.3	
Weight of electrolyte, Lb	2.0	1.7	1.7	
Housing weight, Lb	5.0	4.0	4.0	Incoloy
Ends weight, Lb	6.25	6.25	6.25	ρ = 7.8
Active Electrode Diam D, in.	5.0	5.0	5.0	
Total Electrode Diam d_o, in.	5.5	5.5	5.5	
Thickness/electrode, t, in.	0.062	0.062	0.062	
Electrolyte thickness, in.	0.062	0.062	0.062	
Gas space thickness, in.	0.032	0.032	0.032	

Thus, the average electrode weight/cell = 0.18 pound or

$0.18(d_o^2/5.5^2)(t/0.062)$ for any given diameter and electrode thickness. (a)

Average electrolyte weight/cell = 0.054 pound or $0.054(d_o^2/5.5^2)$ (b)

Average shell weight/cell = 0.13 pound or $0.13(d_o^2/5.5^2)(\rho/7.8)$ for any diameter and metal. (c)

End weight = 6.25 pounds or $6.25(d_o^2/5.5^2)(\ /7.8)$ for any diameter and metal. (d)

If the total voltage required from the generator is E_T and the voltage per cell is E_o:

$$n = \frac{E_T}{E_o} \tag{e}$$

$$\text{Cell weight } (W) = n\,[(a) + (b) + (c)] + (d) = \frac{E_T}{E_o}(a + b + c) + (d) \tag{f}$$

$$d_o = D + 0.5 \tag{g}$$

$$D = 24\sqrt{\frac{P}{I_{CD}E_T}} \tag{h}$$

where P is the power level, watts

I_{CD} is amps/square foot of active area

TABLE IX-1

COMPUTATION OF FUEL CELL WEIGHT AS A FUNCTION OF CURRENT DENSITY FOR 28 VOLTS AND 1 KILOWATT POWER AT 240°C

I_{CD}	E_o	n	D	d_o	$\frac{d_o^2}{5.5^2}$	(a)	(b)	(c)	$\Sigma_{(a)}^{(c)}$	(d)	$n\,\Sigma_{(a)}^{(c)}$	W_{cell}/kw
0 ASF	1.04 v	27										
50	0.98	29	11.38	11.88	4.65	0.84	0.251	0.605	1.70	29.2	49.5	78.7
100	0.93	30	8.03	8.53	2.40	0.423	0.130	0.312	0.865	15.0	25.9	39.9
200	0.87	32	5.65	6.15	1.25	0.225	0.067	0.162	0.454	7.67	14.5	22.2
400	0.79	36	4.01	4.51	0.67	0.121	0.036	0.087	0.244	4.20	8.8	13.0
500	0.76	37	3.6	4.1	0.55	0.100	0.030	0.072	0.202	3.45	7.4	10.85
600	0.73	38	3.26	3.76	0.465	0.084	0.025	0.061	0.170	2.82	6.45	9.3
800	0.66	43	2.83	3.33	0.367	0.066	0.020	0.048	0.138	2.30	5.95	8.25
1000	0.61	46	2.54	3.04	0.306	0.055	0.0166	0.040	0.112	1.92	5.15	7.07

Additional hardware weight associated with fuel cell:

H_2 differential regulator	1.8 Lb
O_2 differential regulator	1.8
H_2 regulator and relief valve	.87
N_2 regulator and relief valve	.87
Solenoid valves (3)	4.26

Total = 30 pounds for 1 kilowatt

N_2 bottle and gas	3.00 Lb
Mounts and brackets	6.00
O_2-H_2-KOH pump & motor	6.00
Condenser	1.50
Voltage regulator	4.00

Assume 50 pounds for 10 kilowatts

TABLE IX-2

CRYOGENIC SYSTEM WEIGHTS AS A FUNCTION OF CURRENT DENSITY

Reversible emf at 240°C = 1.13 volts $\cong$ 1530 watt-hour/pound H_2-O_2

I_{CD}	E_o	Watt-hr/Lb	Lb/kw-hr	Lb O_2/day	Lb H_2/day	S for H_2 2	6	10 days	S for O_2 2	6	10 days
0											
50	0.98	1325	0.755	16.16	2.02	4.27	3.4	3.4	1.258	1.172	1.144
100	0.93	1260	0.795	16.96	2.12						
200	0.87	1180	0.850	18.2	2.27						
400	0.79	1080	0.927	19.8	2.47						
500	0.76	1035	0.968	20.6	2.58	4.0	3.2	2.91	1.237	1.157	1.133
600	0.73	988	1.01	21.5	2.69						
800	0.66	890	1.12	23.8	2.98						
1000	0.61	825	1.21	25.0	3.22	3.8	3.07	2.78	1.22	1.146	1.136

Note: S values (pound system/pound gas) obtained from cryogenic section, Appendix VIII

Example: For I_{CD} = 50, Pounds H_2 system for 2 days = 2.02(4.27)(2) = 17.2 pounds

Pounds O_2 system for 2 days = 16.16(1.258)(2) = 40.6 pounds

Additional hardware weights associated with each cryogenic container:

Fill line	0.1 lb	Pressure controller	0.5 lb
Supply line	0.1 lb	Electric heater	0.3 lb
Vent line	0.3 lb	Temperature controller	0.5 lb
Vent relief valve	1.0 lb	Pressure relief valve	1.0 lb
Vent shutoff valve	1.0 lb	Pressure regulator	2.0 lb
Fill shutoff valve	1.0 lb		

Total hardware for each tank = 7.8 pounds $\cong$ 8 pounds for 1 kilowatt nominal rating.
Assume a value of 10 pounds for 10 kilowatts nominal rating

The cell weight has been computed as a function of current density (I_{CD}) for a total voltage (E_T) of 28 volts and 1 kilowatt power level (P) from the relations shown in (a) to (h). These calculations are shown in tabular form in Table IX-1. They are based on the use of 0.062 inch thick electrodes and an Incoloy shell.

The cell efficiency and therefore the specific fuel consumption are also dependent on the current density. The consumption of oxygen and hydrogen per day for a 1 kilowatt unit is shown as a function of current density in Table IX-2. Also shown are the cryogenic system weights, S (gas plus container per pound of gas) as a function of current density and duration (2,6 and 10 days) for each gas.

From such tabulations as shown in Tables IX-1 and IX-2 the total system weight for a given power level and duration may be readily computed as a function of current density. At an optimum current density the total weight of the system (fuel cell plus fuel plus cryogenic containers plus related fuel cell hardware) is at a minimum. These minimum weights have been summarized for both 1 kilowatt and 10 kilowatts power levels for 1-, 2-, 6-and 10-day missions in Table IX-3.

Table IX - 3

MINIMUM TOTAL SYSTEM WEIGHTS

For 1 Kilowatt

Duration	Weight	
1 day	95 Lb	250 Watt-hr/Lb
2 days	126 Lb	380 Watt-hr/Lb
6 days	246 Lb	585 Watt-hr/Lb
10 days	366 Lb	655 Watt-hr/Lb

For 10 Kilowatts

Duration	Weight	
1 day	386 Lb	620 Watt-hr/Lb
2 days	657 Lb	730 Watt-hr/Lb
6 days	1845 Lb	780 Watt-hr/Lb
10 days	2929 Lb	820 Watt-hr/Lb

APPENDIX X

USE OF CRYOGENICS FOR CO_2 REMOVAL AND/OR DEHUMIDIFICATION

X.1 REMOVAL OF CO_2 BY FREEZING OUT WITH CRYOGENIC H_2

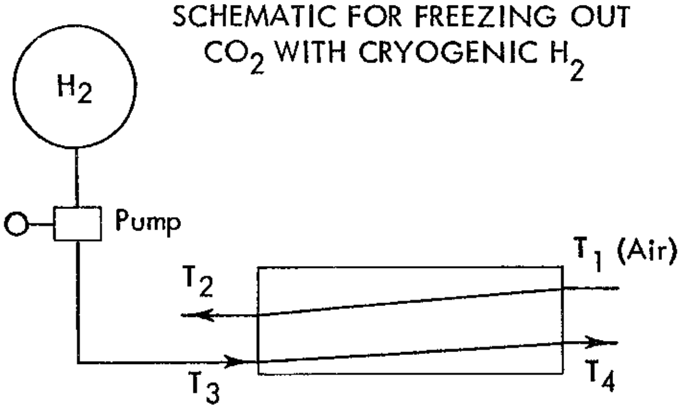
The partial pressure of CO_2 in the cabin air is limited to 4 millimeters mercury, so the air must be cooled below -126.5°C (146.5°K) before CO_2 begins to drop out. The heat to be removed from the air to make this possible must equal the heat picked up by H_2 in the schematic arrangement shown in Figure X-1.

Thus T_3 may be assumed constant and equal to 20°K.

As mentioned above, T_2 must be less than 146.5°K if CO_2 is to condense out.

The mols of CO_2 removed per mol of air depend on the initial concentration and the value of T_2.

The initial concentration of CO_2 in the cabin air is 4 millimeters mercury with a total pressure of 5 psi (259 millimeters mercury).



SCHEMATIC FOR FREEZING OUT CO_2 WITH CRYOGENIC H_2

FIGURE X-1

$$C_1 = \frac{4}{259-4} = 0.0157 \text{ mol } CO_2/\text{mol air}$$

If the concentration of CO_2 in the exit air (at point 2) is C_2,

$$C_2 = \frac{p_2}{259-p_2} \quad \text{where } p_2 \text{ is the vapor pressure of } CO_2 \text{ at } T_2.$$

The vapor pressure of CO_2 is plotted versus temperature and the value of C_2 is plotted versus temperature in Figure X-2.

The mols CO_2 removed/mol air = $C_1 - C_2$. Since 0.1 pound CO_2 must be removed per hour (0.00228 mol), the amount of air to be passed through the exchanger is M_a:

$$M_a = \frac{0.00228}{C_1 - C_2} \text{ mols/hour}$$

VAPOR PRESSURE AND CONCENTRATION OF CO_2 VERSUS TEMPERATURE

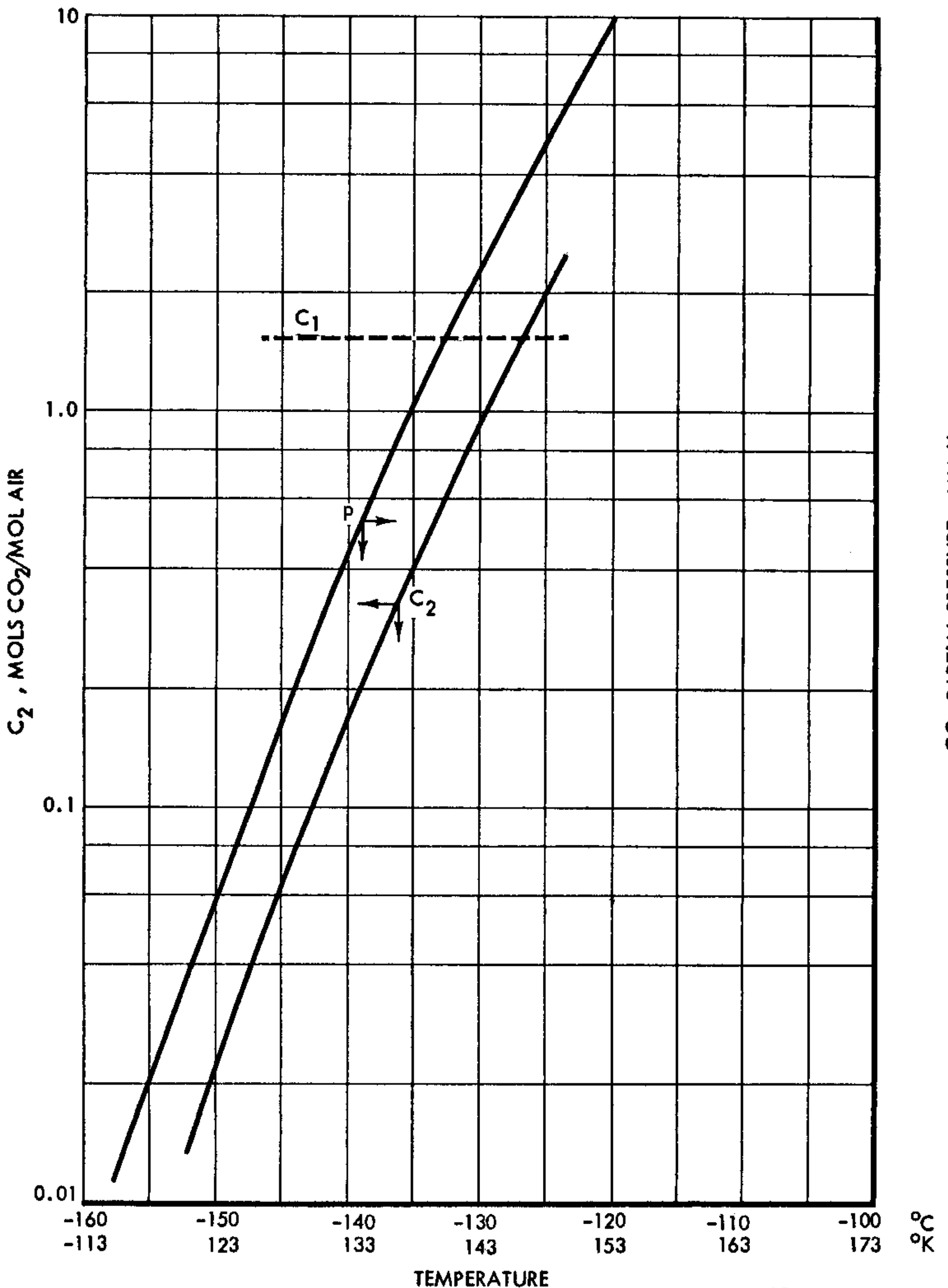


FIGURE X-2

The heat to be picked up by the hydrogen (0.108 pound/hour for one-kilowatt power rating for the fuel cell) is q_H.

$q_H = 0.108\ (h_4 - h_3)1.8$ Btu/hour — where h are the enthalpies (calories/gram) obtained from Figure VIII-3.

$q_H = 0.1945\ (h_4 - 80)$ — h_4 is a function of T_4 and may be found for Figure VIII-3 for various values of T_4.

q_H is plotted versus T_4 in Figure X-3 (shown as dotted line).

The heat to be given up by the air is q_A:

$$q_A = M_a C_{pa}(T_1 - T_2)1.8 + 44 C_2 M_a (h_{CO_2(1)} - h_{CO_2(2)})_{gas} + (C_1 - C_2) M_a\, 44 (h_{CO_2(1)} - h_{CO_{2m}})$$

$$\text{where } M_a = \frac{0.00228}{C_1 - C_2} \text{ (mols of } CO_2 \text{ - free air)} = \frac{0.00228}{0.0157 - f(T_2)}$$

C_{pa} = specific heat of air/pound mol = 7.0

$(h_{CO_2(1)} - h_{CO_{2(2)}})$ gas = enthalpy lost by CO_2 gas carried through uncondensed (Btu/pounds). It can be obtained for any temperature from Figure X-4 .

h_{CO2m} = enthalpy of solid CO_2 at the mean temperature of 140°K, Btu/pound, obtained from Figure X-4. $T_1 - T_2$ = temperature drop, °K or °C

Thus by assuming a value for T_2, the equation for q_A becomes a function of T_1 only. A series of curves of q_A, shown in Figure X-3 by solid lines, is obtained for the indicated values of T_2 and as a function of T_1.

$$q_A = M_a \left[1.8 \cdot 7.0 (T_1 - T_2) + 44 C_2 (h_{CO_{2(1)}} - h_{CO_{2(2)}}) \text{ gas} + (C_1 - C_2) 44 (h_{CO_{2_{1g}}} - h_{CO_{2_m}})\right]$$

$$= M_a \left[12.6\ (T_1 - T_2) + 44 C_2 (h_{CO_{2(1)}} - h_{CO_{2(2)}}) \text{ gas} + (C_1 - C_2) 44 (h_{CO_{2_{1g}}} - 0)\right]$$

$$= M_a \left[12.6 (T_1 - T_2) - 44 C_2 h_{CO_{2(2)_g}} + 44 C_1 h_{CO_{2(1)_g}}\right]$$

WORK DIAGRAM FOR FINDING AIR EXIT TEMPERATURE (T_2)

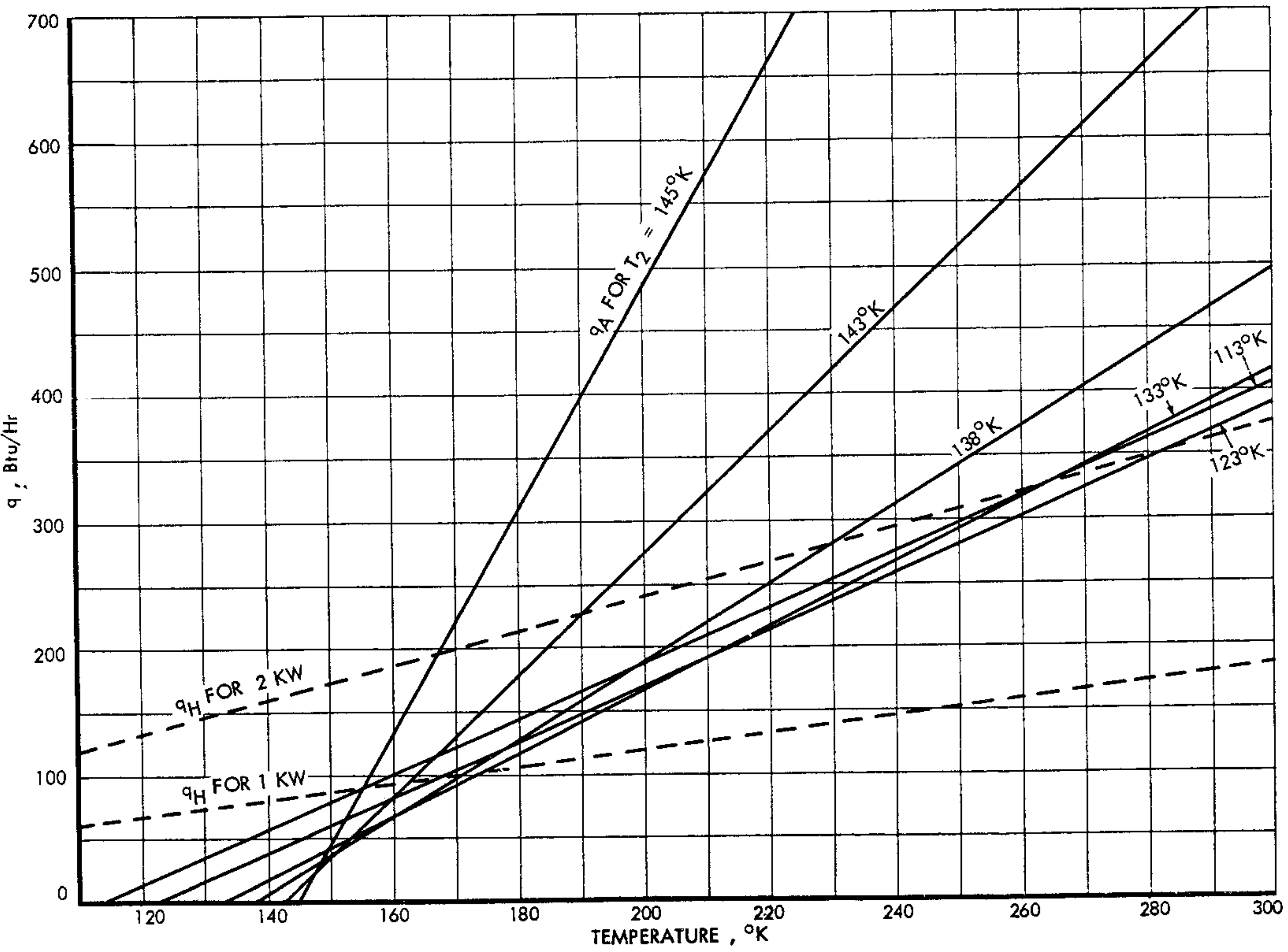


FIGURE X-3

ENTHALPY OF CO_2 VERSUS TEMPERATURE

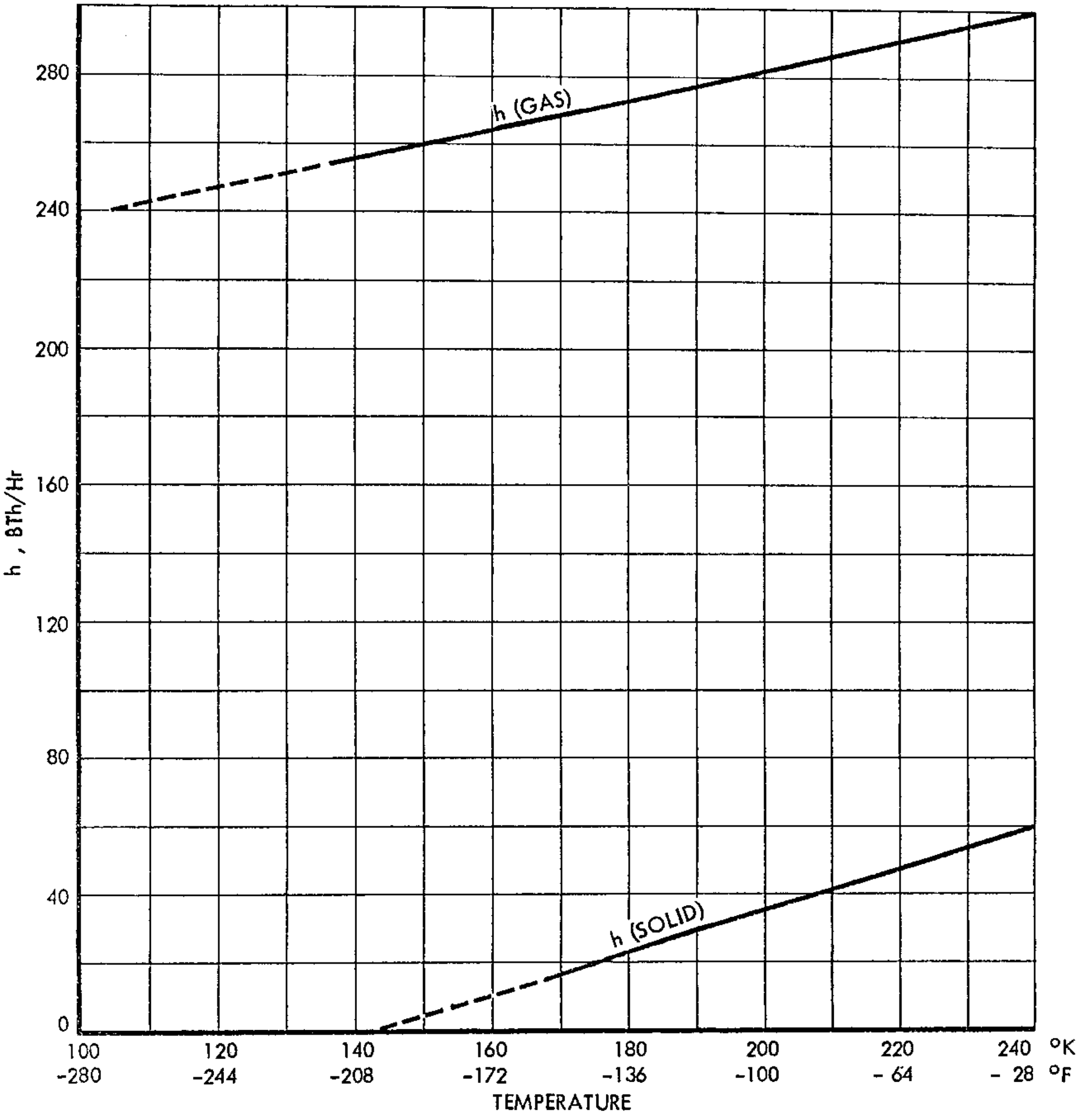


FIGURE X-4

T_2		p_2 mm Hg	C_2(mols CO_2/mol air)	$C_1 - C_2$	$h_{CO_2(2)}$ gas	$44C_2h_{CO_2(2)g}$
-126.5°C	146.5°K	4.0	0.0157	0	258	173
-128	145	3.13	0.0122	0.0035	258	138.5
-130	143	2.31	0.0090	0.0067	257	101.5
-135	138	1.04	0.0040	0.0117	254	44.8
-140	133	0.43	0.00167	0.0140	252	18.5
-150	123	0.06	0.00023	0.0155	248	2.52
-160	113	0.009	0.00003	0.0157	244	0.32

$$q_A = M_a\left[12.6(T_1 - T_2) + 44C_1h_{CO_2(1)g} - 44C_2h_{CO_2(2)g}\right]$$

$$= M_a\left[12.6T_1 + 44C_1h_{CO_2(1)g} - (12.6T_2 + 44C_2h_{CO_2(2)g})\right]$$

Within the temperature ranges that could be assumed for T_1, the enthalpy is a linear function of the temperature. Thus, for any given value of T_2, the equation for q_A is linear with respect to T_1 and determination of two values of q_A versus T_1 will suffice for each value of T_2 assumed.

When $q_A = 0$, $T_1 = T_2$. This becomes one point on the curve. For the second point, assume $T_1 = 200°K$. The following values may be computed for q_A:

T_1	T_2	T_1-T_2	$12.6(T_1$-$T_2)$	$44C_1h_{CO_2(1)g}$	$44C_2h_{CO_2(2)g}$	q_A/M_a	M_a	q_A
200	146.5°K	53.5	675	+194	-173	696	0	-
200	145	55	692	+194	-138	748	0.65	485
200	143	57	717	+194	-101	810	0.34	275
200	138	62	780	+194	- 45	929	0.195	181
200	133	67	844	+194	- 19	1019	0.163	166
200	123	77	970	+194	- 3	1161	0.147	171
200	113	87	1100	+194	0	1294	0.145	188

$h_{CO_2(1)g}$ = 281 Btu/pound

C_1 = 0.0157 mols CO_2/mol air

$44C_1h_{CO_2(1)g} = 44 \cdot 0.0157 \cdot 281 = 194$

Since the heat to be picked up by H_2 must be given up by the air stream, q_H must equal q_A. Allowing ourselves a minimum of 5°K for $T_1 - T_4$ to obtain a reasonably small exchanger area, the following temperatures obtained from Figure X-3 will satisfy the heat balance for one kilowatt-hour use rate for hydrogen:

T_1	T_2	T_4
154°K	145°K	149°K
162	143	157
169	138	164
172	133	167
165	123	160
151	113	146

Any of the above values of the inlet air temperature (T_1) are much lower than cabin air temperatures, so it is evident that a precooler will be required for CO_2 removal by this method if the H_2 use rate is equivalent to one kilowatt. The two-kilowatt use rate curve has also been drawn in Figure X-3. The heat capacity of the H_2 stream for this use rate makes it almost theoretically possible to remove CO_2 from cabin air without precooling. However, any appreciable temperature difference required between T_1 and T_4 would require a certain amount of precooling even at the two-kilowatt power level. Allowing $(T_1 - T_4)$ min = 5°K, a value of 2.2 kilowatts may be extrapolated from Figure X-3 as the minimum use rate for H_2 if CO_2 is to be removed without precooling the air stream.

For the one-kilowatt power level, precooling the air stream for CO_2 removal by cryogenic heat exchanger may be accomplished by either (1) precooling with O_2 heat exchanger, or (2) precooling by heat exchange with the cool CO_2-free air. The choice is to some extent optional but selection of (1) will increase the capabilities of the concept and permit smaller exchanger areas because of the larger heat content available in the respective streams.

SCHEMATIC OF PRECOOLING WITH O_2 HEAT EXCHANGER

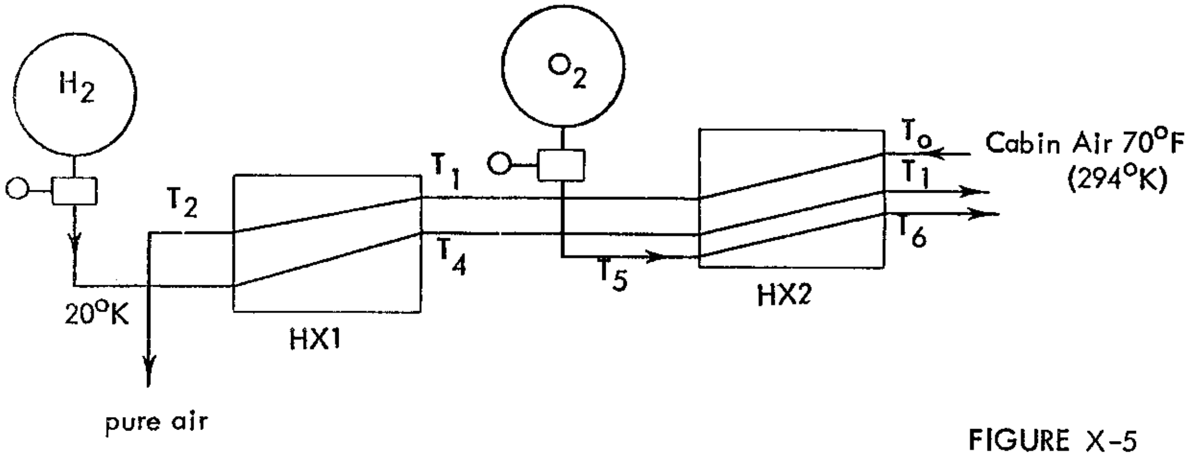


FIGURE X-5

The preceding analysis indicates a maximum temperature of 172°K for T_1. This means that, if expulsion of O_2 from the container by heating is used, the maximum temperature (T_5 max) that could be attained by the O_2 stream leaving the tank would be $T_15 = 167^\circ K$. As shown in Figure VIII-4, only 82% of the O_2 stored can be used if this temperature cannot be exceeded. Theoretically, 67.8 pounds O_2 are required (72 kilowatt-hours and 6 pounds per man). Since $S = 1.2$, the weight penalty would be $1.2\,(67.8/0.82 - 67.8) = 1.2\,(82.8 - 67.8) = 18$ pounds. This penalty may be compared with 9 pounds of LiOH required to handle the CO_2 problem, so obviously expulsion by heating would not be used for the O_2. Therefore, an oxygen pump would be required for the lower power levels (i.e., 1 kilowatt). If pumps are used for both fluids, then the minimum usage rate required using the above arrangement to remove CO_2 and HOH from the system may be computed using a 5°K approach. Thus $T_2 = 25^\circ K$

$$T_7 = 289^\circ K = T_6$$

Enthalpy increase of H_2 and O_2 =

$h_H + h_O$

$h_H = 0.108\,(h_7 - h_{20})\,1.8;\; h_7 = 980$ calories/gram

$= 0.108\,(890 - 80)\,1.8;\; h_{20} = 80$ calories/gram

$= 0.194 \cdot 900 = 174$ Btu/hour

$h_O = 0.9419\,(h_6 - h_5)\,1.8;\; h_6 = 60$ calories/gram

$h_O = 0.9419\,\left[60-(-33)\right]\,1.8;\; h_5 = -33$ calories/gram

$= 158$

$h_H + h_O = 174 + 158 = 332$ Btu/hour

Enthalpy of air stream with cabin air at 294°K

If all of HOH is removed (0.008 pound/pound air)

Δh_{HOH} from HOH 70°F to ice at assumed average of 273°K

$= 1092 + h\text{ fusion} + C_p(294-273)$

$= 1092 + 80 \cdot 1.8 + 0.5\;(294-273)1.8$

$= 1092 + 144 + 19 + 1255$ Btu/pound HOH

For CO_2 at mean temperature of 140^oK:

Δh_{CO_2} from 70^oF to ice at 140^oK = 320 Btu/pound

For air Δh from 70^oF to T = 0.24(294−T) 1.8 Btu/pound

The removal of 0.1 pound CO_2 requires circulation of

$$\frac{0.00228}{0.0157} \cdot 28.9 = 4.2 \text{ pounds/hour of air assuming that } T_2 < 133^oK$$

The removal of 0.1 HOH/hour requires the circulation of $\frac{0.1}{0.008}$ = 12.5 pounds air/hour assuming exit air contains negligible amounts of HOH.

Thus if the above arrangement is used primarily for CO_2 removal, the least amount of heat that has to be removed is from the lowest flow rates and lowest temperature. For all practical purpose (within 1.5%), all of the CO_2 is removed by the time that $T_2 \leq 123^oK$. Thus 4.2 pounds/hour of air must be circulated. To determine the necessary fluid use rate (in terms of P kw) to meet this demand, one has:

$$4.2(294-123)\ 0.24 \cdot 1.8 + 320 \cdot 0.1 + 1255 \cdot 0.008 \cdot 4.2 = 332P$$

$$1.82 \cdot 171 + 32 + 42 = 332P$$

$$310 + 32 + 42 = 332P = 384$$

$$P = \frac{384}{332} = 1.16 \text{ kilowatts}$$

If the above arrangement is used for the removal of both CO_2 and HOH to maintain a satisfactory balance of these components in the environment, the minimum air flow rate is

$$\frac{0.1}{0.008} = 12.5 \text{ pounds/hour}$$

Then the necessary use rate of fluids to meet this demand is approximately:

$$12.5(294-123)0.24 \cdot 1.8 + 32 + 1255 \cdot 0.1 = 332P$$

$$920 + 32 + 125 = 332P = 1177$$

$$P = \frac{1177}{332} = 3.54 \text{ kilowatts}$$

Thus the arrangement of Figure X-5 is inadequate to meet the requirements for either CO_2 removal at use levels below 1.16 kilowatts or removal of both CO_2 and HOH at use levels less than 3.54 kilowatts.

Removal of both CO_2 and HOH for use rates equivalent to less than one kilowatt may be obtained by precooling of the air with the cold pure air stream at T_2 in a third heat exchanger, HX3, as in Figure X-6.

SCHEMATIC FOR REMOVAL OF BOTH CO_2 & HOH FOR USE RATES EQUIVALENT TO LESS THAN ONE KILOWATT

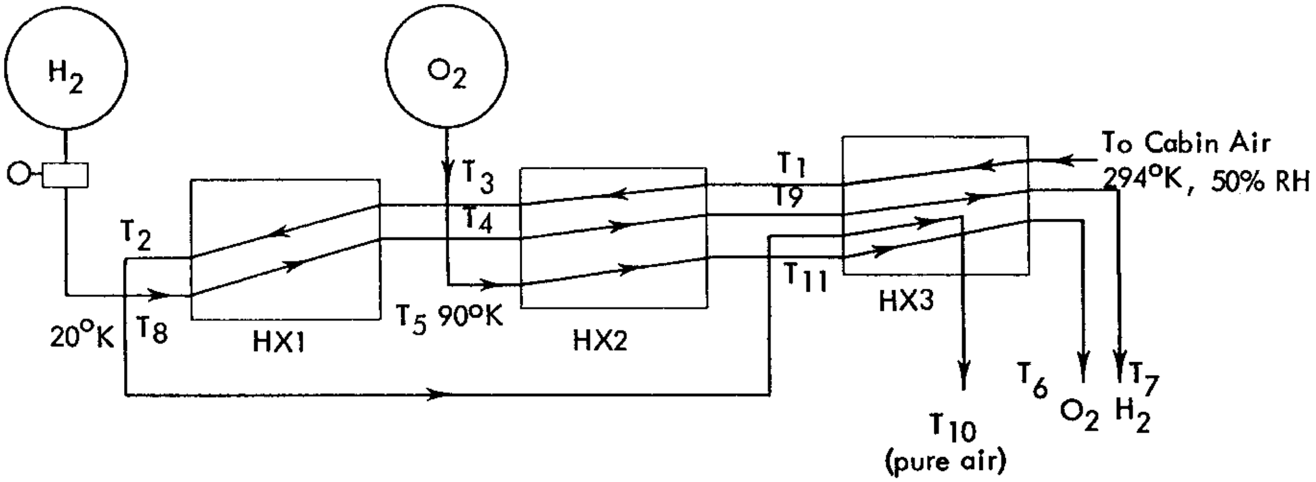


FIGURE X-6

All of the hydrogen and most of the oxygen will be fed to the fuel cell which may be considered outside of the environmental chamber. Thus, the maximum temperature of these streams ($T_6 + T_7$) is dependent primarily on the design of a reasonably small HX3. On the other hand, T_{10} should be as low as possible since it will be fed directly to the environmental chamber and can be used for cooling which in all probability will be necessary. With the lowest value of T_{10} possible, the weight penalties of any cooling system that may be required may be kept to a minimum.

One may determine the minimum cabin cooling available for a one-kilowatt use rate of the fluids using 5°K as the minimum approach, i.e., $T_6 + T_7 = 289°K$:

Enthalpy increase of H_2 stream $= 0.108\,(h_7 - h_8)1.8 + 0.194(980-80) = 174$ Btu/hour

Enthalpy increase of O_2 stream $= 0.942(h_6 - h_5)1.8 + 1.7\,(60+33) = 158$ Btu/hour

Total heat sink for one-kilowatt use rate $= 175 + 158 = 332$ Btu/hour

As before, if the arrangement (Figure X-6) is used for the control of both CO_2 and HOH, the minimum flow rate of air is controlled by the amount of moisture to be removed. Assuming a 5°K approach as a minimum, $T_{10} = 289°K$:

Enthalpy decrease of air $= 12.5(294-289)0.24 \cdot 1.8 = 27$ Btu/hour

Enthalpy stored in frozen H_2O = 125 Btu/hour

Enthalpy stored in frozen CO_2 = 32 Btu/hour

Total enthalpy difference between initial and final states of air = 27 + 125 + 32 = 184 Btu/hour

Since 332 Btu/hour cooling available for 1 kilowatt equals 184 Btu/hour use rate, the minimum use rate for the arrangement of Figure X-6 is

$$\frac{184}{332} = 0.55 \text{ kilowatt}$$

Using a one-kilowatt power level, we may find T_{10}:

$$0.24(294-T_{10})1.8 \cdot 12.5 + 125 + 32 = 332$$

$$(294-T_{10}) = \frac{175}{12.5 \cdot 1.8 \cdot 0.24} = 32.4$$

$$\text{Therefore, } T_{10} = 261.6^{\circ}K$$

Using a flow rate of 12.5 pounds/hour, removal of CO_2 need not be complete, but may be 33% removed per pass. This would allow a vapor pressure of CO_2 in the exit gas of 2.6 millimeters mercury $\cong T_{max} = 144^{\circ}K$. To provide some marginal ΔT, however, the value of T_2 is maintained at 123°K.

The exchanger areas required may be estimated as follows:

Assume $T_2 = 123^{\circ}K$

$T_{10} = 261^{\circ}K$

12.5 pounds/hour of pure air circulated

CO_2 removed in exchanger HX1

$T_4 \cong T_5 = 90^{\circ}K$

$T_9 \cong T_{11} \cong T_2 = 123^{\circ}K$

Balance around HX1:

$$12.5(T_3-T_2)\ 0.24 \cdot 1.8 + 32 = 0.108\ (h_{H4} - h_{H8})1.8$$

$$5.4(T_3 - 123) + 32 = 0.108(332-80)1.8 = 49$$

$$T_3 - 123 = \frac{49 - 32}{5.4}$$

$$T_3 = 126.2$$

Around HX3, latent heat of HOH given up = 125 Btu/hour.

$$125 + 12.5(294-T_1)\ 0.432 = 12.5(261-123)\ 0.432 + 0.942(h_{289} - h_{123})\cdot 1.8 + 0.108(h_{219}-h_{123})_H 1.8$$

$$= 745 + 0.942\ (60 + 19)\cdot 1.8 + 0.108(980-432)1.8$$

$$= 745 + 134 + 107 = 986$$

$$5.4(294-T_1) = 986-125$$

$$294-T_1 = \frac{861}{5.4} = 160$$

$$T_1 = 134^\circ K$$

Around HX2:

$$12.5(T_1-T_3)(0.24\cdot 1.8 = 0.942(h_{11} - h_5)\ 1.8 + 0.108(h_9 - h_4)_H\ 1.8$$

$$5.4(T_1-T_3) = 0.942\cdot 15\cdot 1.8 + 0.108(432-332)1.8$$

$$5.4(T_1-T_3) = 25.5 + 19.4 = 45$$

$$T_1-T_3 = \frac{4.5}{5.4} = 8.35$$

Actually, $T_1-T_3 = 134-126 = 8^\circ$

To compute exchanger areas:

$$\frac{HX1}{\Delta T_m} = \frac{(T_2-T_8) - (T_3-T_4)}{2.3\log\frac{(T_2-T_8)}{(T_3-T_4)}} = \frac{(123-20) - (126-90)}{2.3\log\frac{103}{36}} = \frac{67}{2.3\cdot 0.456} = 64^\circ K = 115^\circ F$$

$$\frac{q}{o} = UA\Delta T$$

$$U \cong 1$$

$$17 = 1\cdot A\cdot 115$$

$$A = 0.145 \text{ square feet}$$

HX2

$$\Delta T_m = \frac{(126-90)-(134-123)}{2.3 \log \frac{36}{11}} = \frac{25}{2.3 \cdot 0.516} = 21 \cdot 1.8 = 38^\circ F$$

$$U \cong 1 \quad \frac{q}{\theta} = UA\Delta T$$

$$45 = 1 \cdot A \cdot 38$$

$$A = 1.20 \text{ square feet}$$

HX3

About 75% of the heat transferred is between the airstreams; therefore:

$$\Delta T_{m_1} = \frac{(T_o-T_{10})-(T_1-T_{11})}{2.3 \log\left(\frac{T_o-T_{10}}{T_1-T_{11}}\right)} = \frac{(294-261)-(134-123)}{2.3 \log \frac{33}{11}} = \frac{22}{2.3 \cdot 0.478} = 20$$

$$\Delta T_{m_2} = \frac{(T_o-T_6)-(T_1-T_{11})}{2.3 \log \frac{T_o-T_6}{T_1-T_{11}}} = \frac{5-11}{2.3 \log \frac{5}{11}} = \frac{6}{2.3 \log \frac{11}{5}} = 7.6$$

$$\Delta T_{m_{av}} = 20 \cdot 0.75 + 7.6 \cdot 0.25 = 17 \cdot 1.8 = 30.6^\circ F \cong 31$$

$$\frac{q}{\theta} = 986 = 1 \cdot A \cdot 31$$

$$A = 32 \text{ square feet}$$

Thus practically the entire exchanger area is in HX3. Since gaseous-gaseous heat exchanger is involved in all cases, the area may be considered predominately fins, both external and internal to the tubing carrying the gases. If a value of 0.425 pound/square foot is used (equivalent to aluminum fins 0.03 inch thick) and 80% fin efficiency, the total weight of the exchangers with a combined area of 34 square feet is:

$$\frac{0.425 \cdot 34}{0.80} = 18 \text{ pounds}$$

Summary of system weights for Figure X-6 is 72 kilowatt-hours (3 days at one kilowatt).

O_2 Storage

$(0.85 \cdot 72) + 6 = 68$ Lb O_2

$S = 1.2$

Therefore, W tank $= 68 \cdot 1.2 = 82$ Lb

Related hardware	=	7.8
		89.8
O_2 pump and water	=	2.0
		91.8

H_2 Storage

$0.108 \cdot 72 = 7.8$

$S = 3.6$

Therefore, W tank $= 7.8 \cdot 3.6 = 28$ Lb

Related hardware	8.4
	36.4
H_2 pump and motor	2.0
	38.4

Totals

O_2 system	91.8 Lb
H_2 system	38.4
Total heat exchange	18.0
Fan and motor	2.0
	150.2
Fuel cell & accessories	30.0
CO_2, O_2, H_2, HOH analyzers	8.0
Total system weight	188.0 Lb

Chargeable to environmental system

$O_2 (6 \cdot 1.2)$ =	7.2 Lb	
O_2 Pump and motor	2.0	to make possible CO_2 removal
H_2 Pump and motor	2.0	
Heat exchangers	18.0	
Fan and motor	2.0	power negligible
Gas analyzers	8.0	
TOTAL	39.2 Lb	

Cryogenic heat exchange may be confined to the dehumidification of the cabin air according to the arrangement shown in Figure X-7. Then the heat to be removed from the air stream must be equal to the heat picked up by the cryogenics at some value of T, W, and X.

SCHEMATIC FOR DEHUMIDIFICATION WITH CRYOGENICS

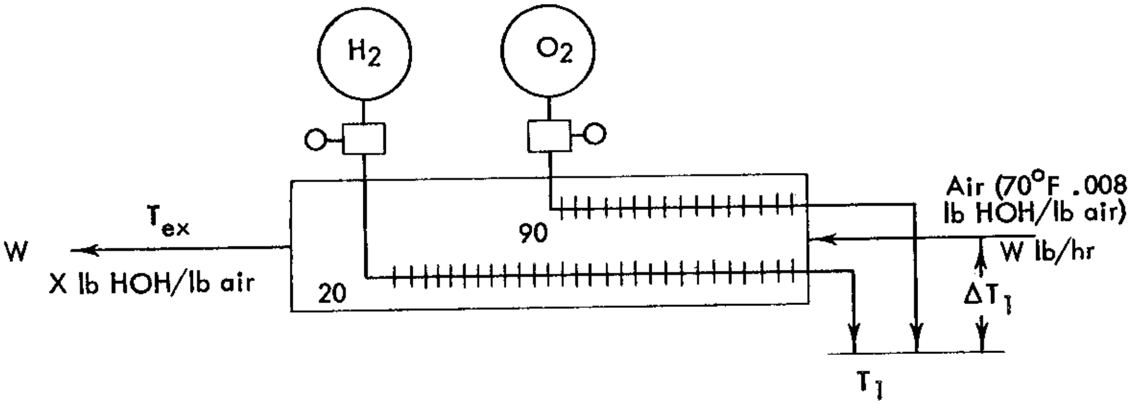


FIGURE X-7

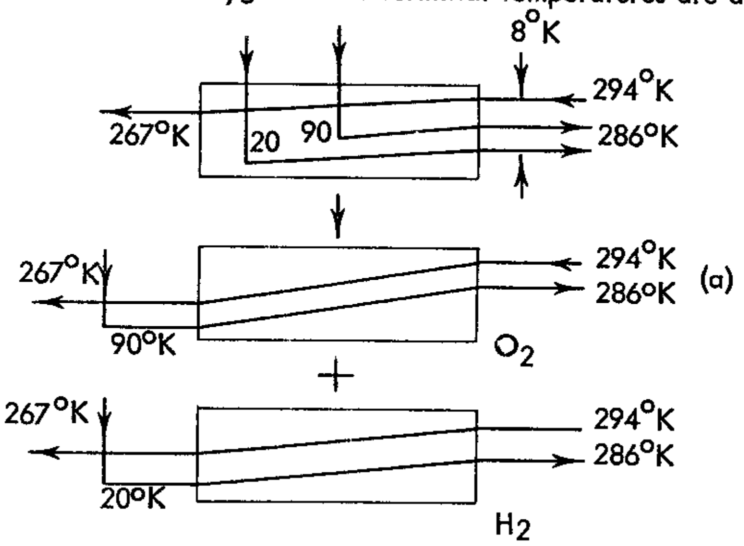
Hydrogen			Oxygen		Available Heat	
T_1	H	Btu/hr	Cal/gm	Btu/hr	Btu/hr	ΔT_1
289°K	976-80 = 896 cal/gm	175	60 + 33 = 93	158	333	5
					332	6.5
					331	8.0
285	964-80 = 884	173	59 + 33 = 92	157	330	9
280	948-80 = 868	170	57 + 33 = 90	153	323	14
270	912-80 = 832	162	55 + 33 = 88	150	312	24
260	884-80 = 804	157	52 + 33 = 85	145	302	34

Air phase

T_{exit}	Lb HOH/Lb air	W	h_{HOH} Btu/hr	h_{air} $W(70-T_{ex})0.24$	$\sum$ h req'd
0°F					
294°K 70°F	.0079				
51°F	.0079	∞	125		∞
40	.0052	37.0	125	267	392
30	.0034	22.0	125	212	337
20	.0021	17.2	125	206	331
10	.0013	15.2	125	218	343
0	.00079	14.1	125	237	362
-30	.000146	12.8	125	307	432

The heats are equal when T_{exit} = 20°F, W = 17.2 pounds/hour, H_{exit} = 0.0021 pound HOH/pound air, and ΔT_1 = 8°K.

To determine exchanger area required, consider heat transferred in two parallel exchangers, one using hydrogen and the other oxygen. The terminal temperatures are as follows:



$$\Delta T_{M_a} = \frac{177-8}{2.3 \log \frac{177}{8}} = \frac{169}{2.3 \log 22.2} = \frac{169}{2.3 \cdot 1.346} = 54.5^{\circ}K$$

$$\Delta T_{M_b} = \frac{247-8}{2.3 \log \frac{247}{8}} \quad \frac{239}{2.3 \log 31} \quad \frac{239}{2.3 \cdot 1.492} = 69.5^{\circ}K$$

$\frac{q}{\theta} = UA\Delta T$ Let $U = 1$

for (a) $\frac{q}{\theta} = 157 = 1.A \cdot 54.5 \cdot 1.8$ $A_a = 1.6$ square feet

for (b) $\frac{q}{\theta} = 173 = 1 \cdot A \cdot 69.5 \cdot 1.8$ $A_b = 1.4$ square feet

Total surface = 1.6 + 1.4 = 3 square feet

At 0.425 pound/square foot exchanger $\cong$ 1.3 pounds.

To check possible thermal resistance of ice formed on surfaces:

k ice = 1.3 Btu/hr/ft^2/$^{\circ}$F/ft

p = 57.5 pounds/cubic foot

for three-day mission, 7.5 pounds ice formed $\frac{7.5}{57.5} \cdot 1728 = 226$ cubic inches

A three-foot thickness of ice $= \frac{226}{3 \cdot 144 \cdot 12} = 0.0435$ feet; $\frac{K}{L} = \frac{1.3}{0.043} = 30$

Thus, resistance of ice $\cong$ 0 in comparison to air film for these conditions. If considered as snow

p = 34.7 pounds/cubic foot k = 0.27

$\therefore L = 0.072$ feet and $\frac{K}{L} = \frac{0.27}{0.072} = 3.8$

If h for gases = 2, $\frac{1}{h_{g1}} + \frac{1}{h_{g2}} + \frac{1}{h_{air}} = \frac{0.5 + 0.5 + 0.26}{1} = 1.26$

$$\text{Thus } \frac{U}{U_o} = \frac{1}{1.26} = 0.79$$

$$A = \frac{3}{0.79} = 3.8 \text{ square feet} \cong 1.6 \text{ pounds.}$$

MOTOR-BLOWER POWER REQUIRED FOR AIR CONDITIONING UNIT

Power requirements for flow through LiOH, using operating data of NRL in five-canister unit (see LiOH section) for five 6-1/2 inch diameter canisters 12 inches long with air flow at 12 CFM (atmospheric pressure) are:

motor-blower rating = 1/12 hp ≅ 62 watts

Assuming 62% efficiency for motor-to-shaft, electrical power input = 100 watts ≅ 20 watts/canister

$$\text{linear velocity} = \frac{12}{\frac{\pi}{4}\left(\frac{6.5}{12}\right)^2} = 52 \text{ feet/minute} = U_o$$

$$P = \frac{\Delta p'' \cdot 62.4 \cdot 746 \cdot \text{CFM}}{12 \cdot 3300} = 1.175\, \Delta p'' \cdot \text{CFM watts}$$

Present flow rates at 5 psi for 17 pounds/hour are:

$$\text{CFM}_1 = \frac{17}{28.9} \cdot \frac{378}{60} \cdot \frac{14.7}{5} = 11.7$$

$$\text{flow velocity} = \frac{11.7}{\frac{\pi}{4}\left(\frac{7}{12}\right)^2} = 45 \text{ pounds/minute} = U_1$$

$$\frac{\Delta P_1}{\Delta P_o} = \frac{L_1}{L_o}\left(\frac{U_1}{U_o}\right)^2 \text{ for comparable flow rates}$$

and $$\frac{P_1}{P_o} = \frac{\Delta p_1}{\Delta p_o} \cdot \frac{\text{CFM}_1}{\text{CFM}_o} = \frac{L_1}{L_o}\left(\frac{U_1}{U_o}\right)^2 \cdot \frac{\text{CFM}_1}{\text{CFM}_o}$$

Using 9 pounds LiOH at 25 pounds/cubic foot results in 16-inch-long column. One and a half pounds activated carbon at 30 pounds/cubic foot results in a 2.5-inch-long column (total = 16 + 2.5 = 18.5 inches).

If only one-half is placed in the unit, the column length is 9.25 inches. Therefore:

$$P_1 = 20 \frac{9.25}{12} \left(\frac{45}{52}\right)^2 \cdot \frac{11.7}{12} = 20 \cdot 0.77 \cdot 0.75 \cdot 0.98 = 11.5 \text{ watts}$$

Considering filter, dehumidifying section, and other miscellaneous losses which double the above, total power requirements for the motor equal 24 watts.

BIBLIOGRAPHY

1. DuBois, E.F., Basal Metabolism in Health and Disease, Third Edition, Lea & Febiger, Philadelphia, Pa., 1937.

2. Hawk, P.B., B.L. Oser and W.H. Summersen, Practical Physiological Chemistry, 13th Edition, Lea & Febiger, Philadelphia, Pa., 1956.

3. Konecci, E.B., "Problems of Respiration and Decomposition With Sealed Cabins," Joint SAE paper 90-B, Specifications in Space Cabin Design, presented at SAE Meeting, Los Angeles, Calif., October 1958.

4. Whitlock, C.M., "Man in Space: Metabolic Data, Stresses Encountered, and Ground Test Facilities," presented at IAS Meeting, Los Angeles, Calif., July 1958.

5. Taylor, C.L., "Human Tolerance for Temperature Extremes," Physics and Medicine of the Upper Atmosphere, University of New Mexico Press, 1952.

6. Rozenblat, V.V., "Pered Poletom v Kosmos," Nauka i Zhizn; November 1956. (Translation: Kriegler, F.J., "Behind the Sputniks, a Survey of Soviet Space Science," Public Affairs Press, Washington, D.C., 1958.)

7. Nau, R.A., "Environmental Control Systems for Manned Space Vehicles," ASME paper 59-AV-11, presented at ASME Meeting, Los Angeles, Calif., March 1959.

8. Dole, S.H., "Environmental Requirements for Extended Occupancy of Manned Satellites," ASME paper 59-AV-12, presented at ASME Meeting, Los Angeles, Calif., March 1959.

9. Williams, R.J., and E. Beerstecher, An Introduction to Biochemistry, D. Van Nostrand Co. Inc., New York, N.Y., 1948.

10. 1953 Guide, The American Society of Heating and Ventilating Engineers, Waverly Press, Baltimore, Md., 1953.

11. Buettner, Konrad, "Heat Transfer and Safe Exposure Time for Man in Extreme Thermal Environment," ASME paper 57-SA-20, New York, 1957.

12. Ingram, W.T., B. Newman, G. Dalevsky and L. Slote, "Exploratory Research on the Theoretical Consideration of Waste Cycles in Closed Ecological Systems," presented at the American Association for Advancement of Science Meeting, Washington, D.C., December 1958.

13. Gradwohl, R.B.H., Clinical Laboratory Methods and Diagnosis, Vol 2, p 1261, C.V. Mosby Co., St. Louis, Mo., 1956.

14. Ingram, W.T., "An Investigation of the Treatment of Cabin Cruiser Wastes," Sewage and Industrial Wastes, Vol 28(1), p 93, January 1956.

15. Luft, Ulrich, "Physiological Limitations in Cabin Environment and Human Adaptations," Physics and Medicine of the Upper Atmosphere, University of New Mexico Press, Albuqerque, N.M., 1952.

16. Robinson, S., and A.H. Robinson, "Chemical Composition of Sweat," Physiological Review, Vol 34(2), p 202, April 1954.

17. Armstrong, H., H. Haeer, and H. Strughold, "Aero Medical Problems of Space Travel," Journal of Aviation Medicine, Vol 20, p 383, 1949.

18. Stambler, I., "Environmental System for Mercury Capsule," Space/Aeronautics, Vol 30(1), pp 22-28, July 1958.

19. Green, C.D., Bioastronautics, Advances in Research, Air University Report Number 4, School of Aviation Medicine, Randolph AFB, Texas, March 1959.

20. Ordway, Fredrich III, Editor, Advances in Space Science, Vol 1, Academic Press, New York, Figure 187, 1959.

21. Dryden, C.E., Artificial Cabin Atmosphere Systems for High Altitude Aircraft, WADC TR 55-353, Wright-Patterson AFB, Ohio, November 1956.

22. Burgess, D., Oxygen Source Components XV, Review of Capacitor Developmental Tests Using Alkali Oxides, US Naval Research Laboratory Report 2153, Washington, D.C., September 1943.

23. Removal of CO_2 from Submarine Atmosphere, Final Report to Bureau of Ships, A. D. Little Inc., Cambridge, Massachusetts, November 1956.

24. Perry, J.H., Chemical Engineers Handbook, Third Edition, Table 197, McGraw-Hill Book Co., New York, 1950.

25. Alexander, Moos, Rapp, and Somer, Continuous Feed Fuel Cell Systems, WADC TR 57-605, Wright-Patterson AFB, Ohio, September 1957.

26. Goldman, D.T., and S.F. Singer, Studies of a Minimal Unmanned Satellite, Part IV, Radiation Equilibrium and Temperature, Report No. 46, University of Maryland Physics Department, College Park, Maryland, June 1956.

27. Hibbs, A.R., The Temperature of an Orbiting Missile, Jet Propulsion Laboratory, California Institute of Technology Progress Report No. 20-294, Pasadena, California, March 1956.

28. Sandorff, P.E., and J.S. Prigge Jr., "Thermal Control of a Space Vehicle," American Astronautical Society Meeting, December 1955.

29. Schmidt, C.M., and A.J. Hanawalt, "Skin Temperatures of a Satellite," Journal of the American Rocket Society, Vol 27, p 10, October 1957.

30. Drummeter, L.F., and M. Schach, Satellite Temperature Control, US Naval Research Laboratory Progress Report, Washington, D.C., May 1958.

31. Hanel, R.A., "Thermostatic Temperature Control of Satellites and Space Vehicles," Journal of the American Rocket Society, Vol 29, p 5, May 1959.

32. Foster, J.F., and J.S. McNulty, "Literature Survey Report for CO_2 Reduction Systems," Contract AF 33(616)-6332, Battelle Memorial Institute, Columbus, Ohio, July 1959.

33. Sammons, J., and E. Chatterton, "Napier Normal Aircraft Diesel Engine," SAE Transactions, Atlantic City, New Jersey, June 1954.

34. Youngren, H.T., "Engineering for Better Fuel Economy," SAE Transactions, White Sulphur Springs, West Virginia, June 1941.

35. Sanders, R.F., "New Chevrolet V-8 Engine," Golden Anniversary SAE Transactions, Detroit, Michigan, January 1955.

36. Obert, E.F., Internal Combustion Engines, International Textbook Company, Scranton, Pennsylvania, 1950.

37. Adamson, J.F., C.E. Burke, and D.B. Potter, "The New American Motors V-8 Engine," SAE Transactions, Detroit, Michigan, March 1956.

38. Scott, Russell B., Cryogenic Engineering, Van Nostrand, New York, N.Y., 1959.

39. "Tables of Thermal Properties of Gases," National Bureau of Standards Circular 564, Washington, D.C., 1955.

40. Nasvytis, A., "Pressure Vessels Made from Sphere and Cylinder Elements," STM-127, Thompson-Ramo Wooldridge, Canoga Park, California, 1958.

41. Roard, R.J., Formulas for Stress and Stain, Third Edition, McGraw-Hill New York, N.Y., 1954.

42. Judge, J.F., "Linde Offers Super Insulation," Missile & Rockets, October 1959.

43. DeHann, J.R., and M. Piccone, Hydrogen-Oxygen Fuel Electrolytic Battery Container Study, WADC TR 58-542, Wright-Patterson AFB, Ohio, October 1958.

44. Jakob, M., and G.A. Hawkins, Elements of Heat Transfer and Insulation, John Wiley and Sons, Inc., New York, N.Y., 1950.

45. Miller, R.R., and V.R. Piatt, The Present Status of Chemical Research in Atmosphere Purification and Control on Nuclear-Powered Submarines, US Naval

46. Air Reduction Company, Inc., Closed Circuit Respiration Metilation System, Phase 1, WADD TR 60-33, Wright-Patterson AFB, Ohio, January 1960.

47. Stutzman, L.F., and W.S. Dodds, Carbon Dioxide Removal from Atmospheric Air in Submarine, Northwestern University, Technological Institute, Evanston, Illinois.

48. Linde Company, Chicago (Personal Communication from Mr. J. Barnes).

49. Reitmeier, R.E., K. Atwood, Carbon Dioxide Absorbents, Girdler Corporation, Report on Contract No. Nobs-50023, Louisville, Kentucky, June 1950.

50. Rossini, F.D., Selected Values of Chemical Thermodynamic Properties, National Bureau of Standards Circular 500, Washington, D.C., February 1952.

51. Hodgman, C.D., Handbook of Chemistry and Physics, 36th Edition, Chemical Rubber Publishing Company, Cleveland, Ohio, p 1630, 1954.

52. Hougen, O.A., and K.M. Watson, Chemical Process Principles, Vol II, Fig 130, p 489, John Wiley and Sons, New York, N.Y.

53. Serin, B. Encyclopedia of Physics, Berlin: Springer Verlag, 1956.