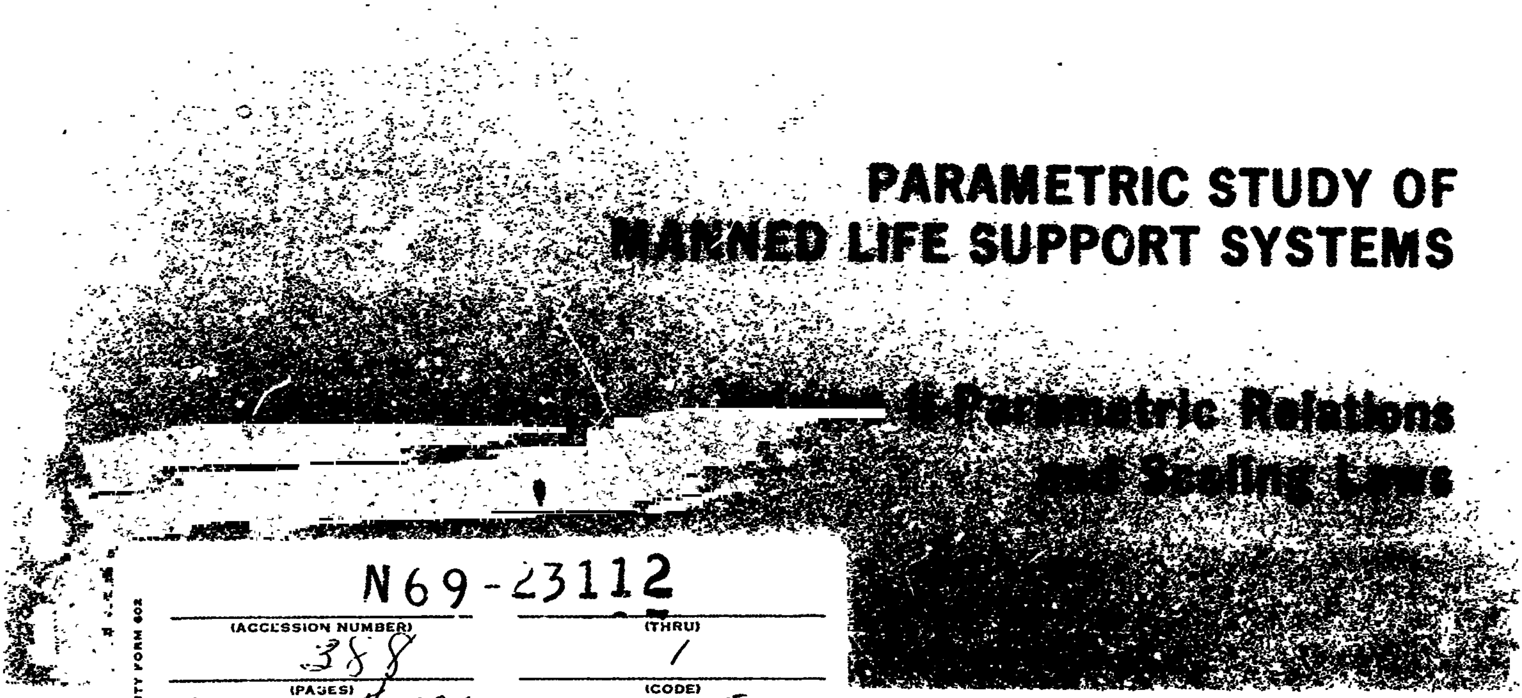


PARAMETRIC STUDY OF MANNED LIFE SUPPORT SYSTEMS

II-Parametric Relations and Scaling Laws

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

MCDONNELL DOUGLAS
CORPORATION

JANUARY 1969

PARAMETRIC STUDY OF MANNED LIFE SUPPORT SYSTEMS

NASA CR 73283

JANUARY 1969

DAC-56713

Volume II-Parametric Relations and Scaling Laws

PREPARED BY
M. M. YAKUT
R. S. BARKER

APPROVED BY:

K. H. HOUGHTON, CHIEF
ADVANCE BIOTECHNOLOGY & POWER DEPARTMENT
RESEARCH AND DEVELOPMENT DIRECTORATE

PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MISSION ANALYSIS DIVISION – OART
MOFFETT FIELD, CALIFORNIA 94035
CONTRACT NAS2-4443

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY
WESTERN DIVISION

MCDONNELL DOUGLAS

FOREWORD

This final report gives the results of a study which developed new parametric analytical tools and a computer program for describing and characterizing life support systems and tradeoffs of subsystems from a mission analysis standpoint. The scaling laws and characteristics developed for each of the life support system components, subsystems, or functional methods were confirmed with equipment data obtained from the latest literature and through a vendor survey. This work was performed by the Advance Biotechnology and Power Department of the McDonnell Douglas Astronautics Company--Western Division (MDAC-WD), Santa Monica, California under Contract No. NAS2-4443 for the Mission Analysis Division of NASA, Office of Advanced Research and Technology, Moffett Field, California. Work was initiated in July 1967 and continued to August 1968 under the direction of Robert S. Barker, Project Manager, McDonnell Douglas Astronautics Company and Joseph L. Anderson, Technical Monitor for the Mission Analysis Division, NASA.

The final report consists of four volumes published in the following breakdown because of physical size and utility for the users:

	Title	Report No.
Volume I:	Summary	DAC-56712
Volume II:	Parametric Relations and Scaling Laws	DAC-56713
Volume III:	Computational Procedures	DAC-56714
Volume IV:	Program Manual	DAC-56715

Contributors to this volume of the report include the following MDAC-WD personnel: R. L. Blakely, E. F. Koprowski, O. C. Ledford, W. G. Nelson, S. W. Nicol, E. W. Pickrel, T. C. Secord, B. N. Taylor, and R. L. Vaughan.

MASTER TABLE OF CONTENTS

VOLUME I: SUMMARY

VOLUME II: PARAMETRIC RELATIONS AND SCALING LAWS

CONTENTS

PRECEDING PAGE BLANK NOT FILMED.

FIGURES

TABLES

Section 1

SUMMARY

The three objectives of this study were to (1) develop parametric data for a range of life support systems with varying degrees of ecological closure, (2) develop the logic to implement these data computationally, and (3) develop the Fortran program to mechanize the computations. The results of the first of these study objectives are summarized herein. The results of the second and third objectives are reported in Volumes III and IV.

Parametric data have been prepared for various functional methods involved in defining, describing, and characterizing the life support subsystems. Empirical, analytical, and engineering design techniques have been used in obtaining these relations. Sensitivity analyses have been performed during the development period to ensure the applicability of the study results to mission analysis studies and to life support system definition and subsystem tradeoff studies. Individual parametric relations, scaling laws, and analytical relationships developed for the component elements and for the eight life support subsystems are presented in terms of equipment weight, volume, size, and required electrical power, cooling, and heating.

PRECEDING PAGE BLANK NOT FILMED.

Section 2
INTRODUCTION

In comparison to the amount of technical effort now being expended in the development of spacecraft life support hardware and equipment which will reclaim or reprocess human waste, there has been considerably less effort at detail evaluation from a mission analysis standpoint of these components and their effectiveness or usefulness in terms of the entire life support system and the complete spacecraft. Therefore, a life support parametric analysis was undertaken to fulfill the following major objectives:

1. Develop parametric data for a range of life support systems with varying degrees of ecological closure.
2. Develop the computational logic to implement the parametric data and their application to life support components, subsystems and fully integrated systems.
3. Develop the Fortran program to mechanize the computational logic.

The results of the first of these study objectives are summarized herein, and the results of the second and third objectives are reported in Volumes III and IV of this report.

Parametric data have been prepared for various functional methods involved in defining, describing, and characterizing the life support subsystems. Analytical, empirical, and engineering design techniques have been performed during the development period to ensure integrity and applicability of the study results to mission analysis studies, and to life support system definition and subsystem tradeoff studies. Individual parametric relations, scaling laws, and analytical relationships developed for the component elements and for each of the eight subsystems that comprise the life support system are presented in terms of equipment weight, volume, size, and required electrical power, heating and cooling.

2.1 APPROACH

The following is a summary of the technical approach used in the accomplishment of this study. Included are the development of parametric relations and scaling laws, the computer program, the sensitivity analyses, and the application of the study results to baseline systems.

2.1.1 Parametric Relations and Scaling Laws

The first major achievement of the study comprised the development of parametric relations and scaling laws for manned spacecraft life support systems based on the best available data. The parametric data presented are applicable to life support systems with various levels of ecological closure and to variations in type of equipment used in accomplishing functions. Variations in life support system specifications include cabin atmospheric constituent combinations and pressure levels and the degree of recovery and reconstitution of wastes to supply water, oxygen, and food. The parametric data are responsive to such variations in mission specifications as crew size, mission duration and purpose, space environment, and resupply period.

For this study, the life support systems are considered to be comprised of eight subsystems: (1) Atmosphere Control, (2) Thermal Control, (3) Water Supply, (4) Waste Management, (5) Food Supply, (6) Crew and Crew Support, (7) Crew Accommodations, and (8) System Controls. Interactions and interdependencies between these various subsystems and other vehicle systems have been investigated and defined. The subsystems are considered to be comprised of functional groups of components and component assemblies which accomplish particular life support functions. For example, in Atmosphere Control, one type of oxygen supply is a functional group of components which reduce carbon dioxide and electrolyze water. The different types of equipment which may be used to accomplish one particular function are referred to as alternate function methods. For example, the Bosch and Sabatier carbon dioxide reduction techniques are alternate functional methods. The parametric data for such descriptive characteristics as weight, volume, or electrical power for each component, or component assembly have been obtained by correlating vendor data and adding appropriate and sufficient engineering designs to these data to obtain an operational system configuration. Current life support hardware data were obtained early in the study from a literature search and by a vendor survey. Well established chemical processes and engineering data also have been used to characterize conceptual systems. Spare parts are determined for the life support subsystems for which estimated component mean time between failure data are available. These include the Atmosphere Control, Thermal Control, Water Supply, and Waste Management Subsystems. The weight and volume of the required spare parts for these subsystems have been determined to satisfy specific reliabilities at specified mission durations.

The required equipment and expendables are determined to provide adequate life support system functions during emergency modes. A total emergency period is specified and this can be considered as either the duration of a single emergency or as the sum total of several emergency periods. Four distinct emergency conditions are considered:

1. Loss of cabin pressure.
2. Failure of liquid cooling circuitry.
3. Failure of liquid heating circuitry.
4. Loss of electrical power.

Emergency condition electrical power, cooling, and heating requirements are determined as well.

2.1.2 Computer Program

The study includes the formulation of the computational logic to perform the required mass and energy balances for interdependent elements which comprise manned life support systems, and to use the results of these balances together with the parametric subsystems hardware data to size individual elements and, ultimately, complete life support systems. Included in the logic is the implementation of an operational Fortran computer program which mechanizes the computational logic and parametric data.

Evaluation of life support alternative systems for tradeoff studies are facilitated by the computing logic which provides variations in mass balance computational procedures due to variations in selected equipment to recover oxygen, water, and food from waste products. The data for components or assemblies of components, that perform particular functions are used in determining the subsystem contributions to total system equipment weight, volume, and required electrical power, cooling, and heating. Weight and volume of supplies or expendables for subsystems and the total system are determined in a similar manner to determining equipment performance and mass balance.

The calculated weights, volume, geometric size, and required electrical power, cooling, and heating for portions of life support systems, as described above, are categorized as quantitative output data. Other data categorized as qualitative output data are also determined. These data include expressions concerning relative confidence level, required development efforts, and unique features for the equipment used in accomplishing the selected functional methods and ecological closure. Quantitative data also include estimates for changes in scientific technology on subsystem weight, and other characteristics at specified flight dates from data upon which the study was based. Projections of the state of the art for critical components most likely to be improved in the next 30 years, from 1970 to 2000, have been used in obtaining these estimated subsystem improvements.

To determine the suitability of given Life Support Systems in performing mission analysis studies, representative solar system missions, space thermal environment, particulate radiation, meteroid flux characteristics, and vehicle configurations are used in the computational logic to obtain the effects and interactions. Weights are determined for (1) required meteoroid shielding to be added to the vehicle structure, (2) required radiation shielding to be provided by equipment and materials within the vehicle and supplemented as necessary by additional material, and (3) any required structure to be added to the vehicle in order to provide adequate life support system space radiator surface area.

2.1.3 Sensitivity Analyses

Sensitivity analyses for two different purposes have been performed during the course of the study. These sensitivities have indicated the effect on the weight, volume, and power of the systems and subsystems from (1) the choice of functional methods, components, and type and degree of parameterized data; and (2) the mission and vehicle requirements. Sensitivity analyses, of the first type, were performed during the preparation of parametric data and during the development of the computer program. These analyses pertain to the work reported in this volume and are discussed with each of the various subsystems. For example, in the Crew and Crew Support Subsystem Section it is shown that it is necessary to specify both crew activity levels and fractions of total crew per cabin in regard to both equipment design and expendable requirements. The equipment is designed for high activity levels and crew allocations in cabins whereas expendable needs are determined on the basis of average daily activity levels and crew size allocations. Differences in these design requirements become especially large for multiple cabin problems or when crew work-rest schedules entail wide variations in activity level. Another example of sensitivity analysis concerns the water and atmospheric gas storage tanks. It is shown in the Atmosphere Control Subsystem section that these storage tanks can become quite large for extended duration missions. To allow realism as well as convenience in location and arrangement of these tanks in planned vehicles, it is desirable to specify and to thus provide the logic permitting appropriate combinations of number of tanks, tank diameter, or tank shape (spherical or cylindrical).

Examples of sensitivity analyses of the second type, mission and vehicle requirements, are reported in Volume III. These analyses were performed after the computer program was developed to obtain the effects of mission and vehicle requirements upon input data and missions, vehicles, and life support systems characteristics.

2.1.4 Baseline Systems

The results of the study have been applied to three complete life support systems called Baseline Systems (see Volume III). Each system provides all the manned daily requirements and needs for existence in a closed module.

The three systems are referred to as and are listed in order of degree of ecological closure:

1. Open System--No recovery of waste materials and food, water and oxygen are supplied.
2. Partially Closed System--Recovery of oxygen and water from wastes; food is supplied.
3. Closed System--Recovery of oxygen, water, and food from wastes; food supplement is provided.

Various levels of ecological closure can be obtained from these baseline systems through formulation of a system by modifications to include functional groups and additions of selected functional methods. Thus, systems can be analytically defined intermediate to the open and partially closed systems and intermediate to the partially closed and closed systems.

The results of the study, including the parametric relations and scaling laws and the supporting engineering analyses are presented in the international system of units (SI). English units have been parenthetically included throughout this volume to aid those who are unfamiliar with the SI in the comprehension of the technical discussion of the life support subsystems and processes involved.

To enable the user of the study results to easily find the data which defines a particular life support subsystem or component, Table 2-1 lists the subsystem, its functional items, and for each, the figure or equation number of the relevant parametric data.

This volume of the report includes the following major chapters:

- Mission and Vehicle Criteria (Section 3).
- Parametric Relations and Scaling Laws (Section 4).
- Conclusions (Section 5).

Table 2-1

PARAMETRIC DATA AND ANALYTICAL RELATIONSHIPS

Subsystem	Functional Item	Parametric Data and Analytical Relations
Atmosphere Control	High-pressure atmospheric constituents storage	F 4-4, 4-5, 4-[illegible] 4-[illegible]
	Cryogenic storage	F 4-[illegible], 4-1[illegible], 4-11 and 4-12 through 4-[illegible]
	Atmosphere supply distribution system	E 4-27
	Cabin pressure controls	T 4-[illegible]
	CO_2 reduction	
	Bosch	T 4-11 through 4-14
	Molten carbonate	T 4-15, 4-16
	Solid electrolyte	T 4-17, 4-18
	Sabatier	T 4-19 through 4-24
	Water electrolysis	
	Rotating cell with H_2 diffusion	T 4-25
	Double membrane cell with H_2SO_4 electrolyte	T 4-26
	Water vapor cell	T 4-27
	Membrane cell with KOH electrolyte	T 4-28
Thermal Control	Cabin wall insulation	E 4-28 through 4-32
	Atmosphere cooling equipment	
	Cabin heat exchanger and fan	F 4-35, 4-36, 4-38, 4-39
	Condenser	Subsection 4.3.3.2
	Water separator	E 4-47, 4-48
	Blower and compressor	E 4-50, 4-51, 4-52, 4-53
	Ducting and miscellaneous equipment	E 4-58, 4-59, 4-60, 4-61
	Atmosphere circulation fan	E 4-54, 4-55, 4-56
	Cooling and heating loops	
	Interface heat exchanger	E 4-105
	Water evaporator	E 4-96, 4-97
	Cold plates	E 4-99, 4-100
	Tubing	E 4-110, 4-112
	Pumps	E 4-114, 4-115, 4-116
	Space radiator	Subsection 4.3.3.1
	Miscellaneous equipment	E 4-119, 4-120, 4-121, 4-122
Water Supply	Water storage tanks	E 4-12[illegible], 4-125, 4-126, 4-12[illegible], 4-12[illegible]
	Sterilization equipment	E 4-1[illegible]1, 4-1[illegible]2, 4-1[illegible]4
	Tubing, pumps, and miscellaneous equipment	E 4-1[illegible]5 through 4-1[illegible]
	Water recovery	
	Air evaporation	T 4-[illegible]2
	Electrodialysis	T 4-34, 4-3[illegible]
	Vapor pyrolysis	T 4-3[illegible]
	Multifiltration	T 4-41
	Vapor compression	T 4-42
Waste Management	CO_2 removal	
	Lithium hydroxide	T 4-44
	Liquid absorption	T 4-45
	Electrodialysis	T 4-47
	Solid amines	T 4-50
	Carbonation cell	T 4-52
	Molecular sieves	T 4-55
	Trace contaminants removal	T 4-56, 4-57
	Urine collection	E 4-152 through 4-160
	Urine transfer and storage	E 4-161 through 4-167
	Fecal collection, storage, and processing	E 4-168 through 4-181
	Refuse collection and storage	E 4-182 through 4-190
Food Supply	Stored food	T 4-59
	Processed food	
	Glycerol process	T 4-62
	Hydrogenomonas process	T 4-65
Crew and Crew Support	Space suits and clothing	T 4-69
	EVA support equipment	T 4-71
	First aid and medical equipment	T 4-73
	Personal items and hygiene kit	T 4-75
	Instrumentation and controls	T 4-77
Crew Accommodations	Living and recreational equipment	T 4-79
	Gravity conditioning equipment	T 4-80
	Instrumentation, controls, and lighting equipment	T 4-8[illegible]
Controls	Total control subsystem	E 4-192, 4-193

NOTE: *F denotes Figure, E denotes Equation, and T denotes Table

Section 3
MISSION AND VEHICLE CRITERIA

The life support system, being one of many systems which support the functions of a space vehicle and enable it to accomplish its mission, interacts with and must meet the needs or restrictions imposed by these systems as well as be sensitive to the effects of the environment and what emergencies may occur. This section discusses the mission requirements and vehicle implications which were considered. The mission requirements include (1) representative Earth orbital and interplanetary trajectories from which determinations may be made of space environmental characteristics; (2) crew physical characteristics and activity levels; (3) considerations of regular resupply intervals; and (4) operation modes.

Vehicle requirements considered include the rationale concerning compartmentation, the allocation and location of the life support system equipment to the several cabins, and the integration of the life support system with the other vehicle systems.

3.1 MISSION REQUIREMENTS

In a parametric type of analysis, it is rather difficult to deal with all the various mission requirements which might be considered. To assess the effects of these requirements, representative Earth orbital and interplanetary missions have been selected. These permit making evaluations for the effects of mission durations, resupply intervals, and emergency conditions and modes of operation. These evaluations will be general and parametric as possible to make their effects upon the life support system broad and the results determined least restrictive. The subject of the space environment, although it is part of the mission requirements, is treated as a complete subject in Section 3.2.

3.1.1 Space Missions

The life support systems to be considered in this study were to be applicable to space missions from the present to the end of the century. The various manned missions that have been considered for this time period range from Earth orbits to lunar explorations and in to Mercury and out to Jupiter. The Earth orbital missions considered extend to several years and include resupply periods and crew tour-of-duty periods of up to 1 year. The minimum lunar mission, Apollo, is for 7-day duration and will be dependent upon the size of the colony on the moon. Representative interplanetary missions have been selected that consist of missions in to Venus and Mercury and out to Mars and Jupiter. The vehicle solar spatial locations versus the time in flight have been used to designate these missions. They are shown in Figures 3-1 through 3-4.

The representative interplanetary missions give a basis for the space environment. By integrating the time history, the meteoroid flux may be established. At particular stages of a mission, such as planetary swingby, evaluations are made for the design of the spacecraft thermal control. These environmental heating conditions provide heat fluxes between average or maximum values. Solar flare effects are determined for the planetary missions on a statistical basis and involve the vehicle flight path and anticipated solar flare activity. The Earth orbital missions range from near orbits to synchronous and from equatorial to polar inclinations. Geomagnetically trapped radiation levels with superimposed anticipated solar flare activity are determined for the Earth orbits. For Earth orbits, resupply periods and crew duty periods may range up to 1 year, and the specified tour of duty is used as the exposure period in the analyses. The range of mission durations specified are from 7 to 1,800 days or from lunar missions to Jupiter missions.

3.1.2 Expendable Requirements

Expendable materials are those items which may be resupplied or disposed of such as food, water, atmospheric gases, and empty food packaging. Materials and equipment which are considered to be resupplied during Earth orbital missions are treated as expendables. Materials for use during emergency

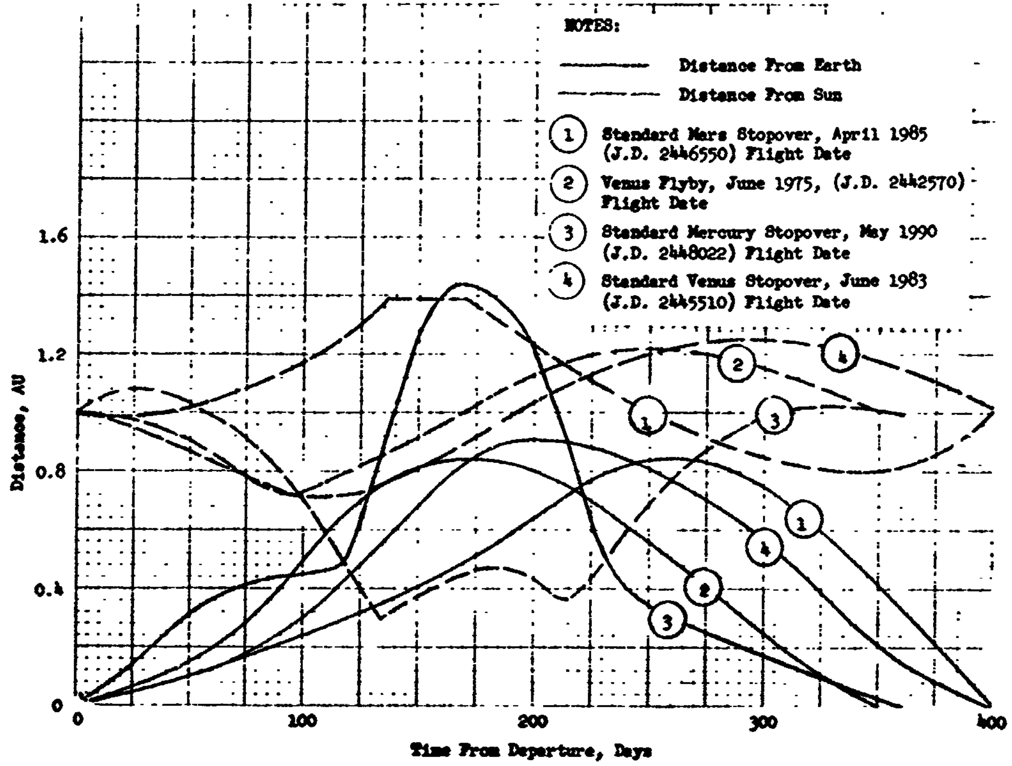


Figure 3-1. Mars, Mercury, and Venus Missions (Distance/Time History)

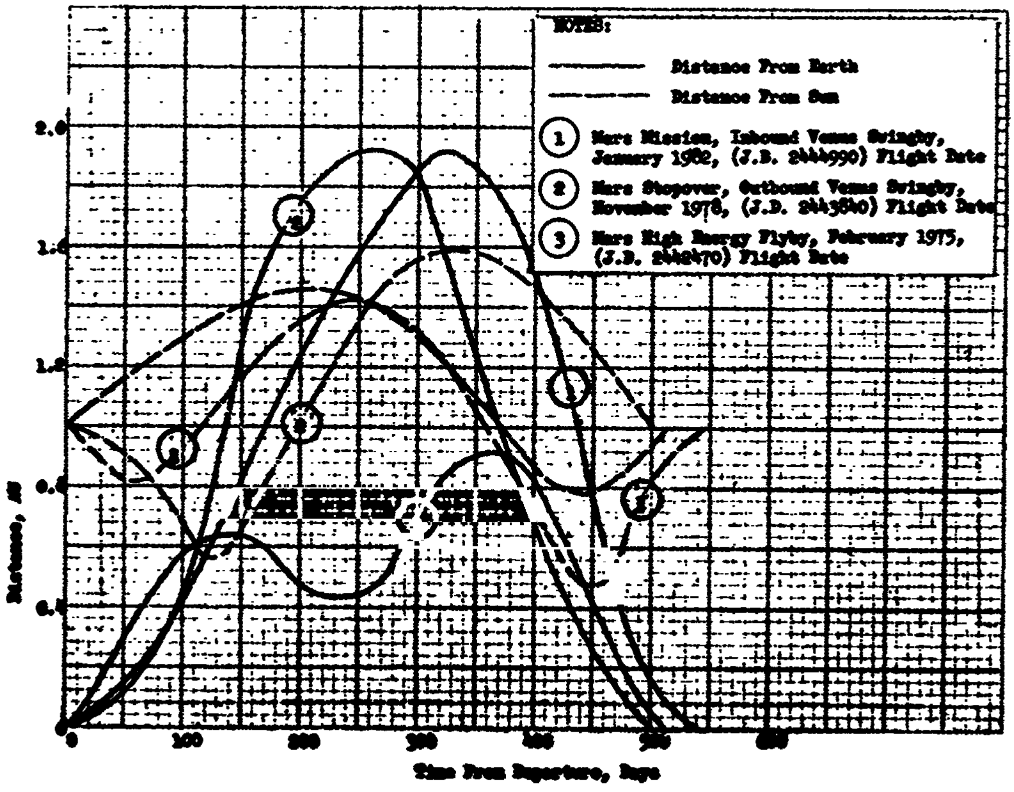


Figure 3-2. Mars and Venus Missions (Distance/Time History)

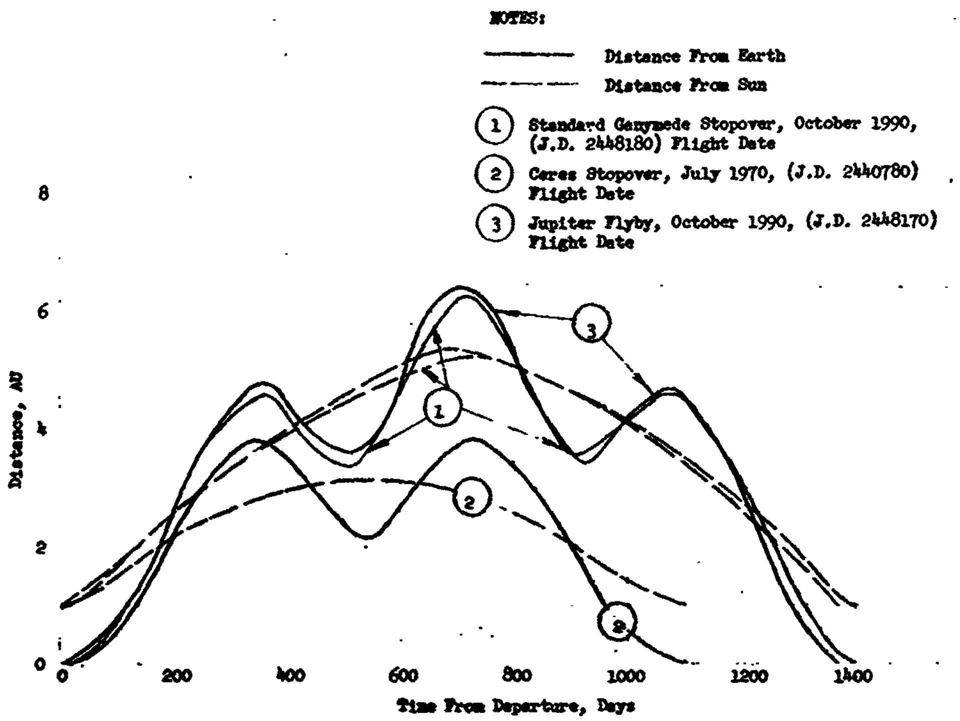


Figure 3-3. Ganymede, Ceres, and Jupiter Missions (Distance/Time History)

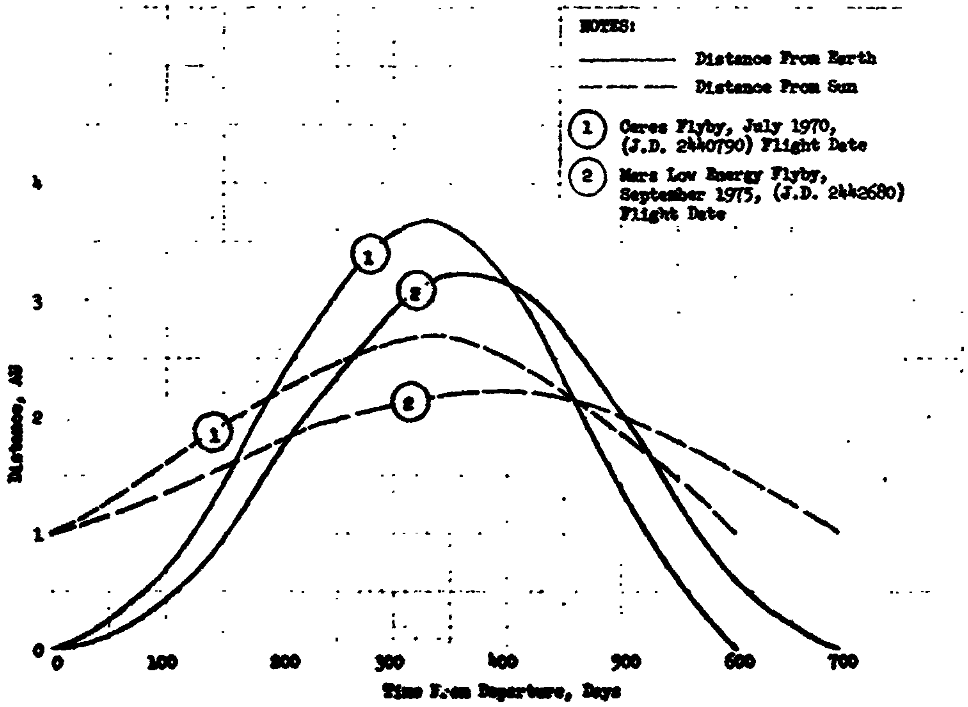


Figure 3-4. Ceres and Mars Missions (Distance/Time History)

modes or equipment for repair purposes are not considered to be expendable, but instead they are considered separately. The expendable requirements are determined for each subsystem, and they are totaled in the same manner as the subsystem characteristics of weight, volume, or power. The expendable items considered for each life support subsystem are specified in Table 3-1.

3.1.3 Emergency Modes

The primary emphasis in the life support system requirements for coping with emergencies has been directed to those emergency modes which may prevail for some protracted time period. These emergencies may involve failure of life support system equipment, vehicle structure, or other vehicle equipment. This interest in emergency operation has been especially prompted by the high weights of the supplies required to satisfy extended emergency periods. Some emergencies which are more easily related to number of occurrences rather than to time periods have also been considered in the study. These emergencies include such items as medical emergencies and small fires.

Table 3-1

SUBSYSTEM EXPENDABLE MATERIALS AND EQUIPMENT

Subsystem	Expendable Materials and Equipment
Atmosphere Control	Stored atmospheric gases and the storage vessels. Miscellaneous materials used in oxygen recovery processes such as catalyst for CO_2 reduction and electrolyte for water electrolysis.
Thermal Control	Stored water for water evaporator.
Water Supply	Stored water for drinking, food preparation, washing, and fecal collection. Miscellaneous materials used in water recovery such as pre-treatment and post-treatment chemicals.
Waste Management	Collection devices and containers for urine and fecal materials. CO_2 removal materials such as LiOH and liquid absorbent. Activated charcoal for trace contaminants removal, housekeeping supplies.
Food Supply	Food and food containers
Crew/Crew Support	None
Crew Accommodations	None
System Controls	None

There have been four basic emergency conditions related to an emergency period which are accounted for in the computational logic:

1. Loss of cabin pressure.
2. Failure of liquid cooling loop and/or the radiator loop.
3. Failure of liquid heating loop.
4. Loss of electrical power.

The following discussion describes the operation of the life support system and the equipment under a given emergency, and what equipment and supplies are necessary to maintain the safety of crew and vehicle during the emergency period.

An emergency period is specified for each case, but it has been assumed that the sum total of emergency periods are limited to a maximum of 30 days. The specified emergency period may be considered to be either a cumulative total of several emergency periods or one continuous emergency period. Emergency equipment, required power, heating, cooling and supplies are sized to accommodate each of the four emergency conditions for the specified emergency period.

Of the four emergency conditions, the one which has the most immediate and direct effect upon crew safety is the loss of cabin pressure. This condition can occur as a result of meteoroid puncture, structural failures, [illegible]rposely for extinguishment of major fires. For emergencies involving th[illegible]ss of cabin pressure or failures of the cooling system, the crewmen are assumed to don their space suits and are considered to have their suits connected to the atmosphere purification loop. This loop is modified so that it may serve the suit loop function. The crewmen are assumed to be intermittently performing at high metabolic rates presumably due to operational requirements dictated by procedures for terminating the emergency and returning the space vehicle to normal operation conditions.

With loss of cabin pressure, equipment which is completely cooled by convective heat transfer to the cabin atmosphere could no longer operate this way except to transfer heat to the inner cabin wall. This condition might be possible if the heat could be transferred through the cabin wall and rejected to space; however, the heat, or at least part of it, is reradiated from the cabin inner wall and objectionable overheating of equipment and crewmen occurs. Determinations for such conditions are beyond the scope of this study; but instead a simplified criterion is used--most life support system equipment that is normally convectively cooled by the cabin atmosphere is considered to be inoperative during emergency conditions. This equipment is primarily that used in the recovery of oxygen, water, and food. Rather than provide the logic which permits alternate functional methods such as cooling by liquid coolant to be used during emergency periods, the approach has been taken to assume that all recovery processes are inoperative during any of the four assumed emergencies.

Emergency power, heating, and cooling requirements are determined on the basis that these recovery processes are inoperative, and emergency power is assumed to satisfy all other normal continuous power requirements. The equipment and expendables for use during these emergency operations are determined on the basis of several assumed short emergency periods with the cumulative total of these equal to the specified emergency period. Particular features of the requirements and operational characteristics for individual, affected, life support subsystems under emergency conditions are given in the following paragraphs.

3.1.3.1 Atmosphere Control Subsystem

As noted above, the oxgyen recovery processes are assumed to be inoperative. Since airlock usages are provided for these periods on a normal basis, it is assumed that this number of airlock uses is sufficient for the emergency period airlock requirements.

Atmosphere gases for emergency periods are assumed to be supplied from high pressure storage sources. The discussion of reasons for not considering cryogenic storage for these periods are presented in Subsection 4.2.2.2. The emergency oxygen and diluent are stored in separate tanks. These tank capacities are sized from the crew oxygen use rate based on the specified metabolic rate and number of crew per cabin, and on the specified cabin leakage and airlock use rate. Beside the emergency atmospheric gas requirements, the atmospheric gases required for the specified cabin repressurizations also are contained in the emergency tanks.

3.1.3.2 Thermal Control Subsystem

It is assumed that emergency cooling is provided through use of a water evaporator which vents its steam to space. Heat is transferred to the water in the evaporator by flowing emergency loop coolant through a heat exchanger in the evaporator. This emergency coolant loop interfaces with and handles the needs for those liquid cooled components which are assumed to be operative during emergency conditions. These include the dehumidifying condenser and one of the alternate emergency period CO_2 collectors in the atmosphere purification loop.

As the crew members are in suits during emergency periods, they are cooled by being connected to the atmosphere purification loop. The oxygen requirements and the flow rate are based on suit ventilation requirements. A booster type compressor is added to satisfy the additional pressure losses for components such as filters, LiOH bed (if specified), ducting, and the condenser/water separator in the suit loops and, therefore, the atmosphere purification loop may operate at normal conditions at all times. A dehumidifying condenser is sized for emergency suit loop operation and it is compared with a condenser sized for normal atmosphere purification loop operations and the larger condenser of the two is selected for the subsystem. If partially isothermal molecular sieve/silica gel beds are specified for emergency periods, their emergency heating and cooling requirements must be satisfied.

3.1.3.3 Water Supply Subsystem

Water storage and distribution equipment are assumed to be operational during emergency periods; however, the water recovery units are inoperative. Water required for crew drinking and food preparation purposes during emergencies is determined and is added to the normal stored water needs. Water tankage is thus sized to accommodate both stored water for normal operations and stored water for emergency operations. The stored water may be sterilized by a pasteurization method, and this heat is normally convectively transferred from the surface of the storage tanks to the cabin atmosphere. Problems associated with this type of heat transfer during emergency cabin depressurizations have been discussed above. This heat quantity is small, and it is assumed that these tanks are heated normally during emergency periods without any adverse overheating effects to either the water tanks or to adjacent equipment and crewmen.

3.1.3.4 Waste Management Subsystem

Collection methods for urine and fecal material under emergency conditions are assumed to be the most simple and reliable methods of those considered in this study. These are manual, personal urine and fecal bags.

When oxygen is not being recovered in the specified life support system, normal carbon dioxide collection may be accomplished by one of three methods: LiOH beds, adiabatic molecular sieve/silica gel beds, or partially isothermal molecular sieve/silica gel beds. These methods are also considered to be suitable for use during emergency conditions. If the emergency periods are long, the regenerable beds provided by the latter two methods are more suitable on the basis of weight because they do not require expendable materials. However, the LiOH method could be preferred for emergency periods on the basis of reliability. This method is certainly the most reliable as it is essentially passive with no modulation valves or other active elements.

Trace contaminant removal equipment is assumed to be in normal operation during the emergency periods.

3.1.3.5 Food Supply Subsystem

Normal stored food would be used in a normal manner for the emergency period. If the life support system includes food processing equipment, this is assumed to be inoperative during emergency periods, and sufficient food would be included to meet the required emergency duration needs.

3.1.3.6 Crew and Crew Support Subsystem

As noted above, crewmen are assumed to be wearing their space suits and connected to the atmospheric purification loop. The crewmen are assumed, during emergencies, to be performing at high metabolic rates for short time periods within the total specified emergency period. These high metabolic rates size the suit loop equipment for heat, water vapor, and CO_2 removal and for adequate suit ventilation.

The high metabolic rates are determined (Section 4.3) on the basis of an assumed rate of 1,000 Btu/hour for 50 percentile crewmen. The corresponding total metabolic heat for other percentile crewmen is determined by multiplying this reference value by the ratio of basal metabolic rate for the crew percentile at hand to the basal metabolic rate for 50 percentile crewmen. The latent and sensible heat load portions of the metabolic rates are determined through the assumptions that suit outlet drybulb and dewpoint temperatures are 88° and 80°F, respectively, and suit inlet flow is saturated at 50°F. The CO_2 generation rate is determined by multiplying the computed normal CO_2 generation rate by the ratio of the reference emergency period metabolic rate of 1,000 Btu/hour to the normal metabolic rate.

In these determinations, it is assumed that the crewmen in their space suits are distributed in the vehicle cabins according to the specified expendable design distribution. Expendables for emergency operation are based on the crew expendable design distribution and activity levels. Crew support items such as first aid, medical supplies, and EVA support requirements which are determined on the basis of the overall mission are assumed to be sufficient to satisfy emergency period requirements.

3.1.3.7 Crew Accommodations and Controls Subsystems

For these two subsystems, no additional requirements, beyond those determined on the basis of overall mission input data are determined.

3.2 SPACE ENVIRONMENT

This section contains parametric data and mathematical relationships which are used in determining space environmental characteristics of importance to the life support system and the protection of the crew. These environmental characteristics include particulate and thermal radiation and meteoroid flux.

Particulate radiation data are presented for geomagnetically trapped radiation, individual solar flares as attenuated by the geomagnetic field, galactic cosmic radiation, and statistical solar flare effects. The data are presented in terms of dosage, expressed in units of REM (roentgen-equivalent-man), as functions of aluminum shield thickness. Equivalent shielding ratios provided by other materials relative to aluminum are specified. Solar flare dosages for Earth orbital missions are based on the 12 November 1960 solar flare event. This was a relatively large solar flare event and was well documented. The statistical solar flare events are used for interplanetary mission radiation shielding determinations. The last solar cycle (1951 to 1961) flare events were used as the model in obtaining these data. As such, dosages as functions of aluminum shielding thickness are presented for maximum and minimum solar activities and for various probabilities that the predicted dosage will not be exceeded.

The mathematical relations used in computing heat transfer through vehicle walls and energy rejected by space radiators are developed. The radiative heat transfer processes involved are based on the assessment of the spacecraft thermal environment. Both Earth orbital and interplanetary flights are considered. View factors, relating radiative exchange between the sun, planets, and vehicles, are included. The mathematical relationships used in the computations for determining effective space "sink" temperatures are developed. The sink temperatures are used in sizing thermal insulation assemblies for walls of occupied cabins and in sizing life support system space radiators. These are the radiators used to reject to space the heat generated by crewmen, life support system equipment, and other specified equipment not for life support system.

Mathematical relationships used in estimating meteoroid flux, meteoroid penetration, and shielding requirements are presented. Computation of shielding is determined for walls of occupied cabins and for protection of space radiator tubes.

3.2.1 Particulate Radiation

The radiation hazards of manned spaceflight are due to the ionizing radiation encountered in space. For Earth orbital missions, the charged particles trapped in the Earth's magnetic field (i.e., protons and electrons) present the greatest biological problem. For interplanetary flight, the proton constituent of galactic cosmic rays and solar cosmic rays form the greatest biological problem. Other space radiation, e.g., alphas, heavy nuclei, X-rays, gamma rays, radiowaves, and the solar wind (low energy protons), are much less of a biological problem and are adequately attenuated once protons, the principal sources, are sufficiently shielded.

Parametric radiation dose data for various manned orbital and interplanetary missions have been determined. This work includes a considerable range of low-altitude Earth orbits as well as the synchronous orbit; namely, 200, 400, 600, 1,500, and 19,350 nmi at inclinations of 28.5°, 50°, and 90°. The data presented are parametric in nature and include not only the integrated dose per day for the geomagnetically trapped radiation, but also the dose per year or dose as a function of mission duration for interplanetary radiation sources, e.g., galactic cosmic and solar cosmic rays.

3.2.1.1 Methods of Analysis

The shielding analysis was performed in two distinct phases: (1) determination of the space radiation environment for the above typical specified missions, and (2) calculation of basic dose attenuation data for each mission.

The energy spectrum of planetary-trapped protons and electrons was established by computations using the latest available space environment data as incorporated in an MDAC-WD developed program called OGRE (Reference 3-1). This program transforms the geographic coordinates of a given orbit into the geomagnetic coordinate system and then sums the time-weighted particle fluxes that a vehicle would encounter over the mission profile.

For the calculation of basic dose attenuation data, an MDAC-WD developed program called CHARGE (Reference 3-2) was used. The CHARGE program is a primary calculational tool for computing dose as a function of shield thickness for each primary and secondary radiation source. For these calculations, an idealized spherical shell type shield of aluminum is assumed. The calculated doses are in units of REM. To accomplish this, the normal dose units of radiation absorbed dose are converted to REM by using energy dependent quality factors (Q. F.) for neutrons and protons. For electrons and bremsstrahlung radiation a Q.F. of 1.0 was used (Reference 3-3).

Exponential dose buildup factors for aluminum were used in the attenuation of bremsstrahlung radiation to account for the scattered components.

3.2.1.2 Parametric Results

Geomagnetically Trapped Radiation Dosage - Orbital Missions

Figures 3-5 through 3-7 present the basic dose attenuation data generated by CHARGE for geomagnetically trapped radiation, i.e., trapped protons, trapped electrons, and electron-bremsstrahlung secondary radiation. These data cover circular orbits of 200, 400, 600, 1,500 and 19,350 nmi, at inclinations of 28.5°, 50°, and 90°.

It is readily seen that the dosage for the low Earth orbits increases significantly with increase in orbit altitude. At synchronous orbit, trapped electrons and electron-bremsstrahlung radiation are the chief sources of radiation dose and trapped protons are negligible. This is because the trapped proton dosage peaks at 1,500 nmi and becomes negligible at approximately 8,000 nmi.

Solar Flare Radiation Dosage - Orbital Missions

Figures 3-8 through 3-12 present orbit-averaged solar flare radiation dose, for the orbit altitudes mentioned, using the 12 November 1960 solar event as a model. This flare is classified as a 3+ event, was the largest of a group of large events, and was well documented. Using this flare spectrum, an assessment was made of orbit dose at various inclinations, i.e., 35°, 45°, 50°, and 90°. It is not shown but it should be noted that for the 200, 400, and 600 nmi orbits, solar flare radiation cannot penetrate the geomagnetic field at low inclinations of 0° to 28.5°. No data are presented for these inclinations, and in fact, the dosage at 35° for these orbits are quite low compared to the dosage indicated in 45°, 50°, and 90° orbits.

Galactic Cosmic Radiation

Galactic cosmic rays consist of very energetic nuclei whose composition is approximately 85% protons and 15% alphas and higher atomic nuclei stripped of their electrons. The range of energies extends from a few MeV to 10^{19} MeV with an average energy of 4 BeV. The dose per year from galactic cosmic rays, considering its proton component only, is presented in Figure 3-13. It is readily apparent from this figure that to shield against

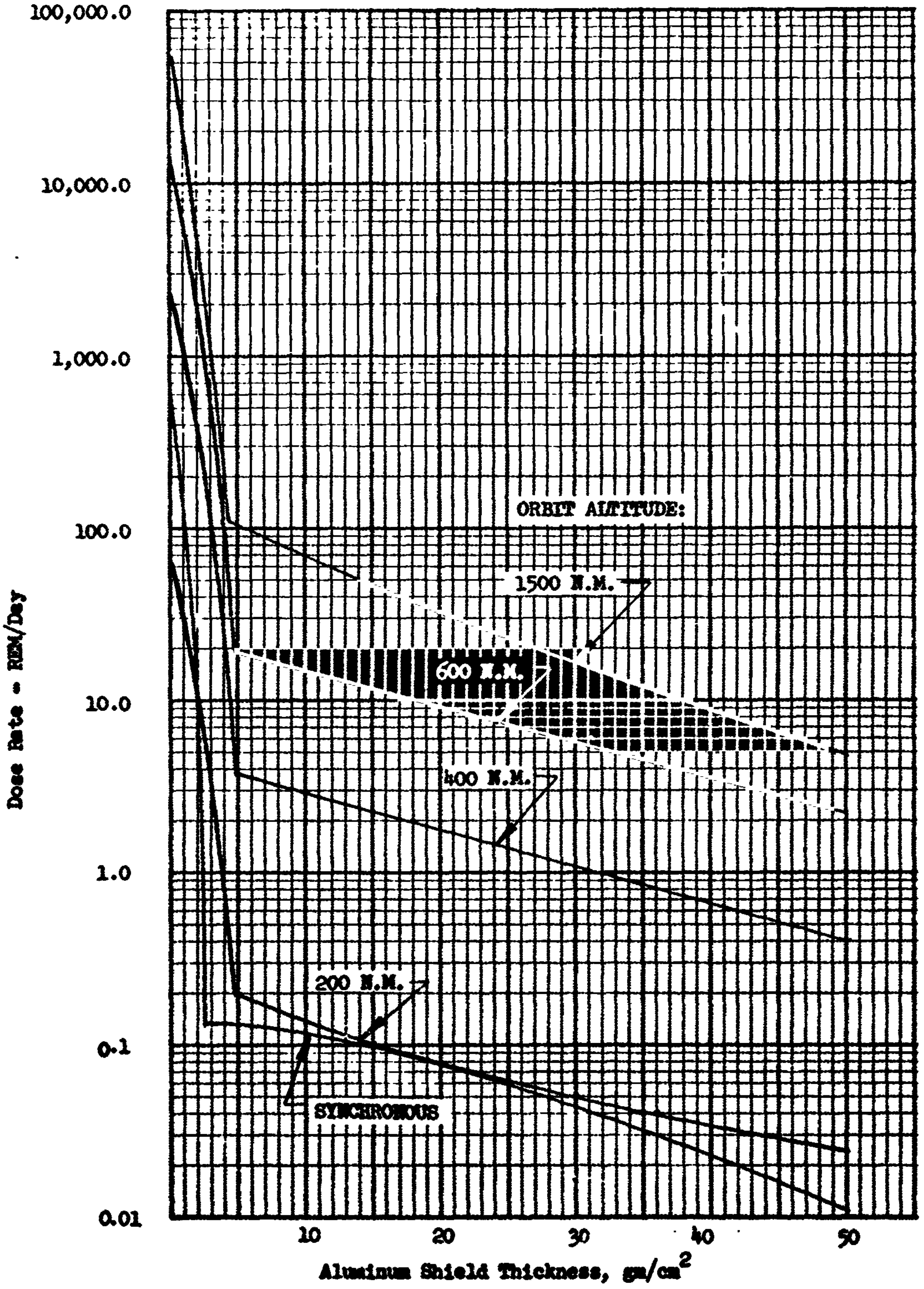


Figure 3-5. Dose Rate for Geomagnetically Trapped Radiation at 28.5° Inclination

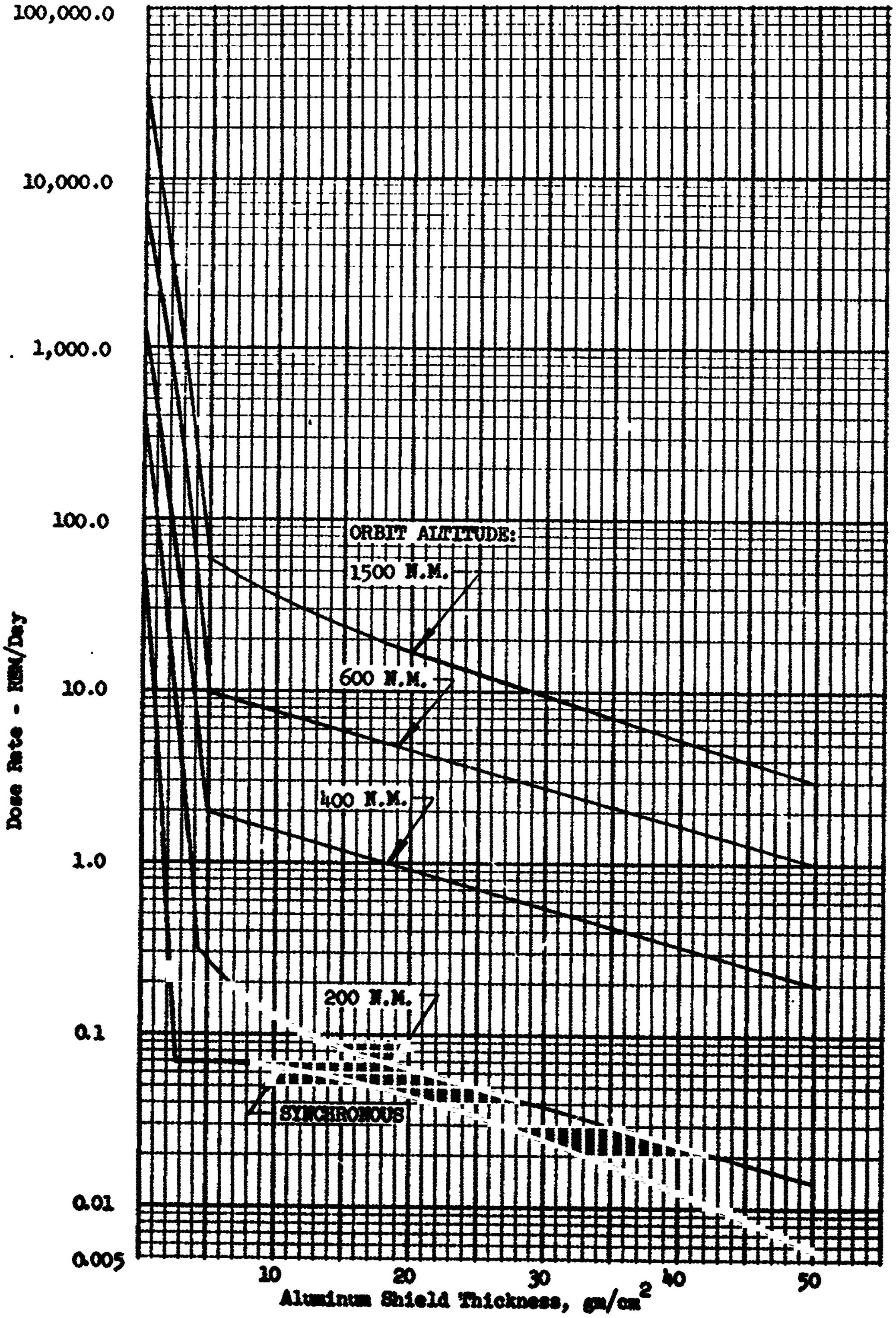


Figure 3-6. Dose Rate for Geomagnetically Trapped Radiation at 50° Inclination

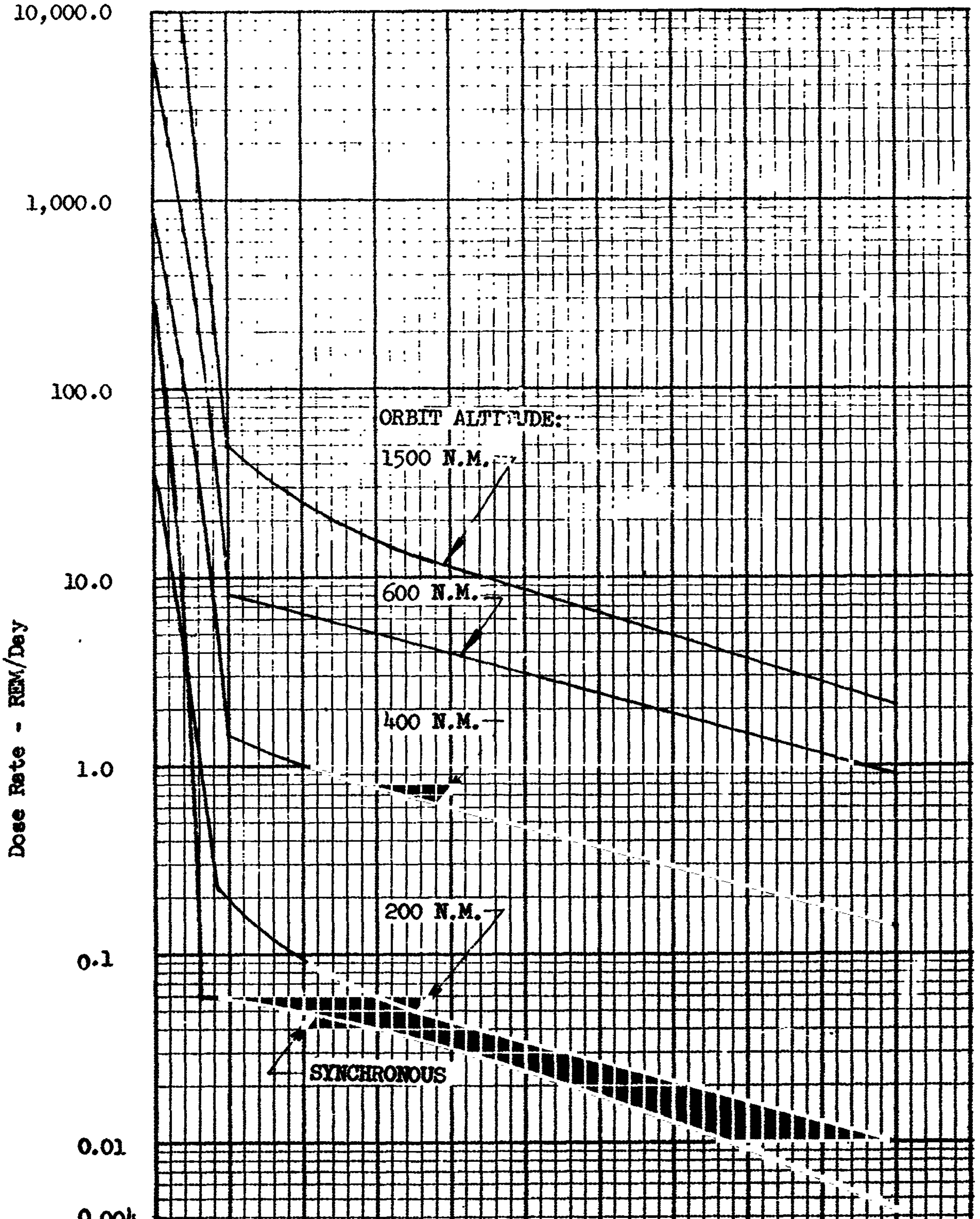


Figure 3-7. Dose Rate for Geomagnetically Trapped Radiation at 90° Inclination

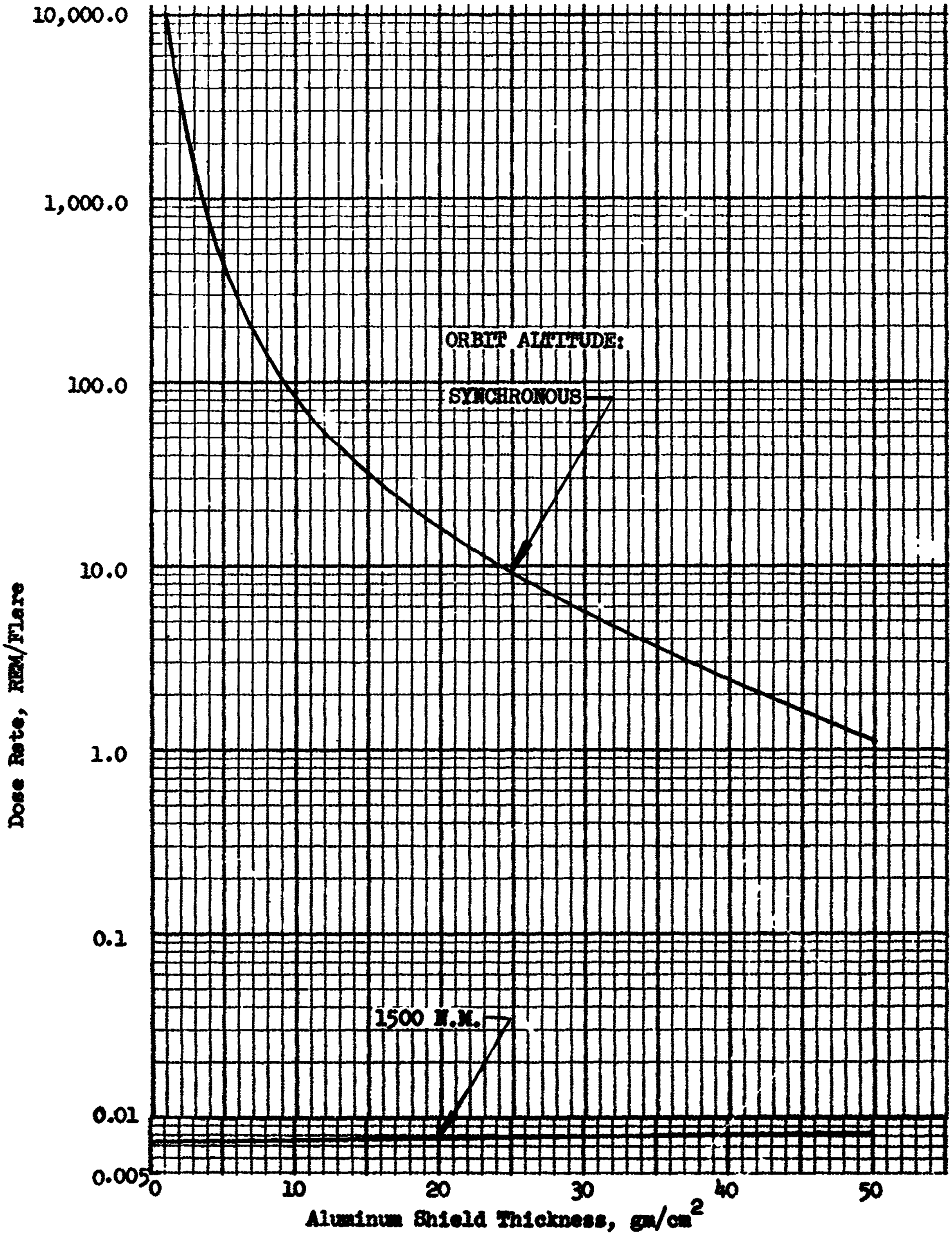


Figure 3-8. Dose Rates for Solar Flares During Earth Orbital Missions at 28.5° Inclination

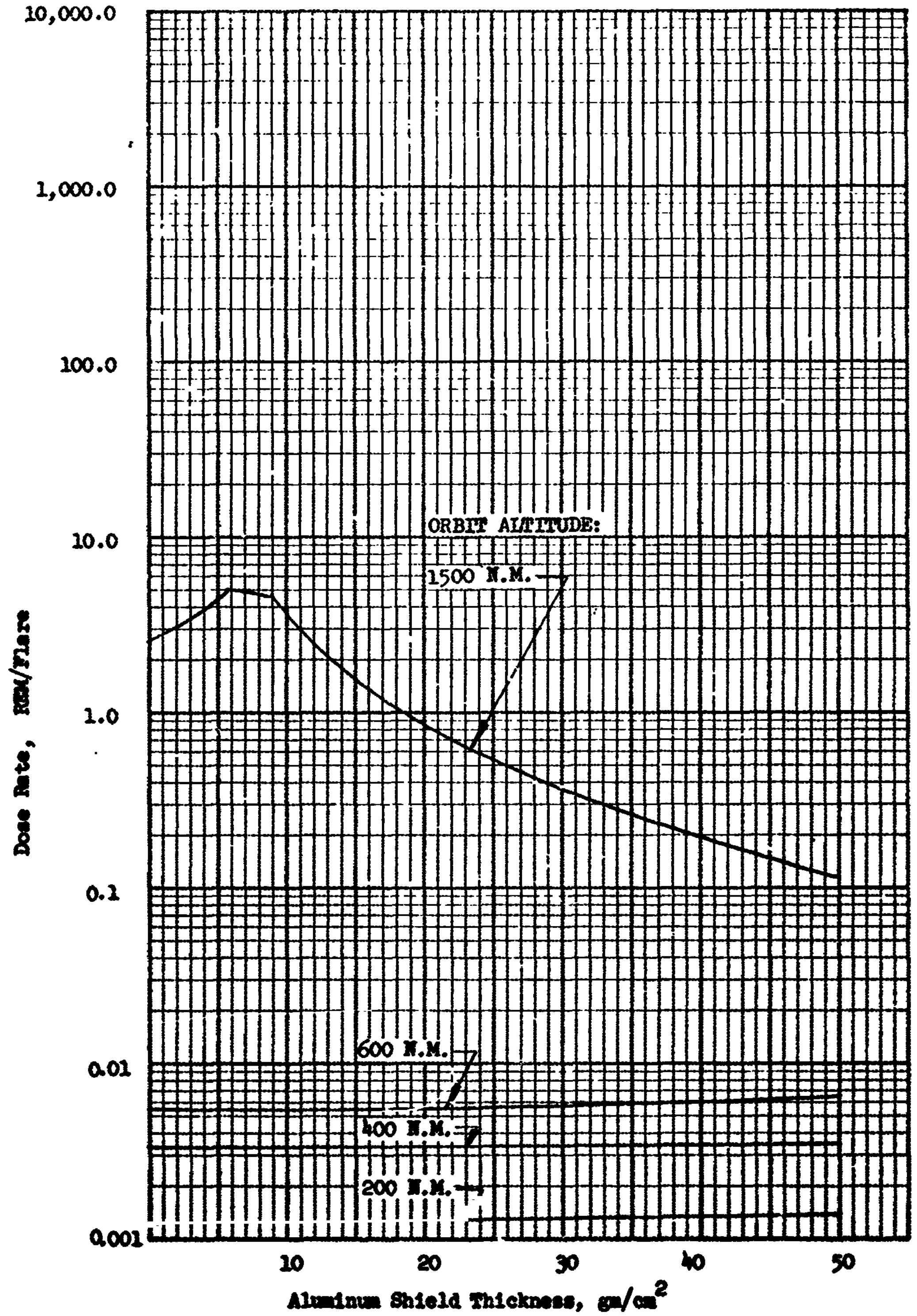


Figure 3-9. Dose Rates for Solar Flares During Earth Orbital Missions at 35° Inclination

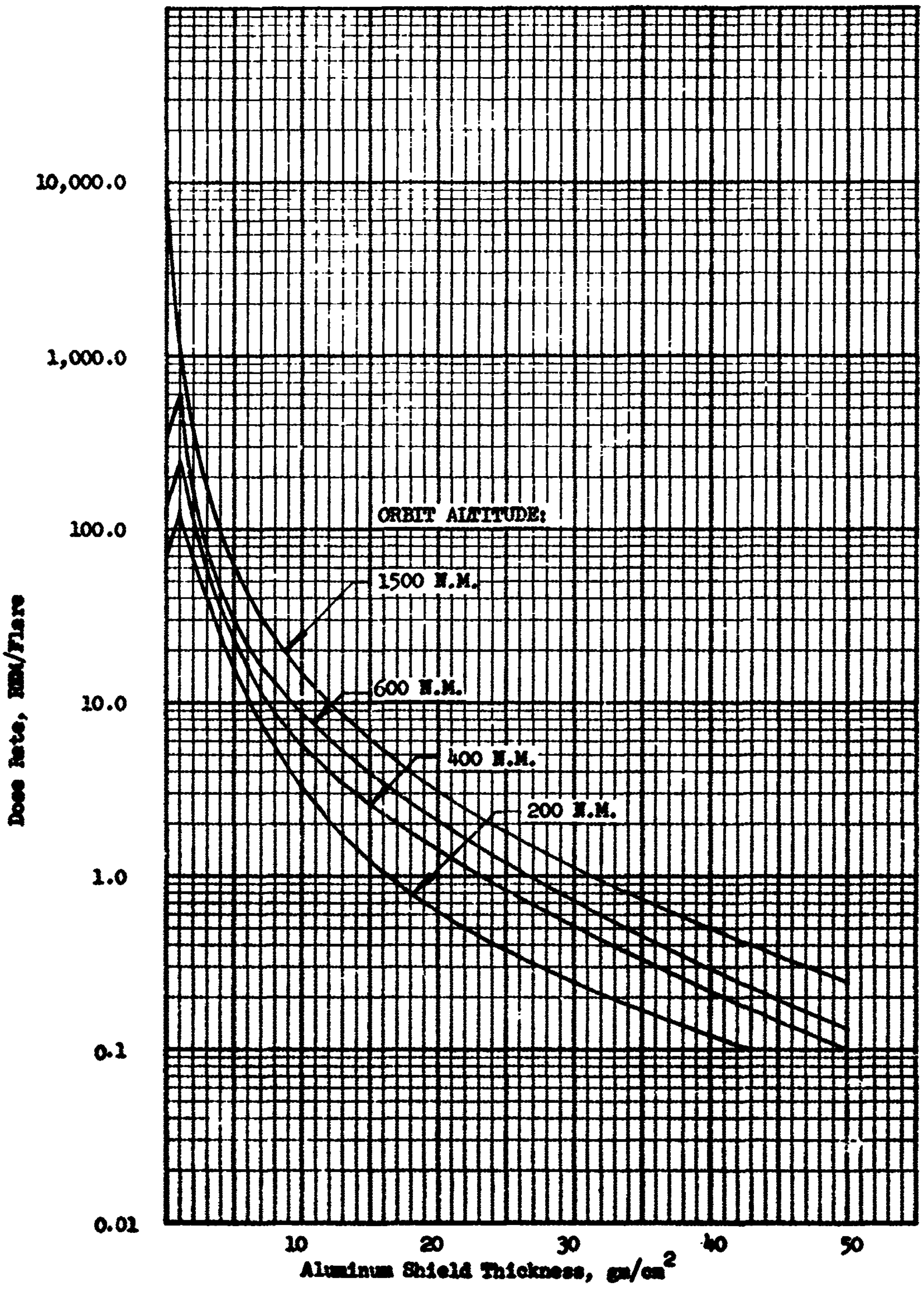


Figure 3-10. Dose Rates for Solar Flares During Earth Orbital Missions at 45° Inclination

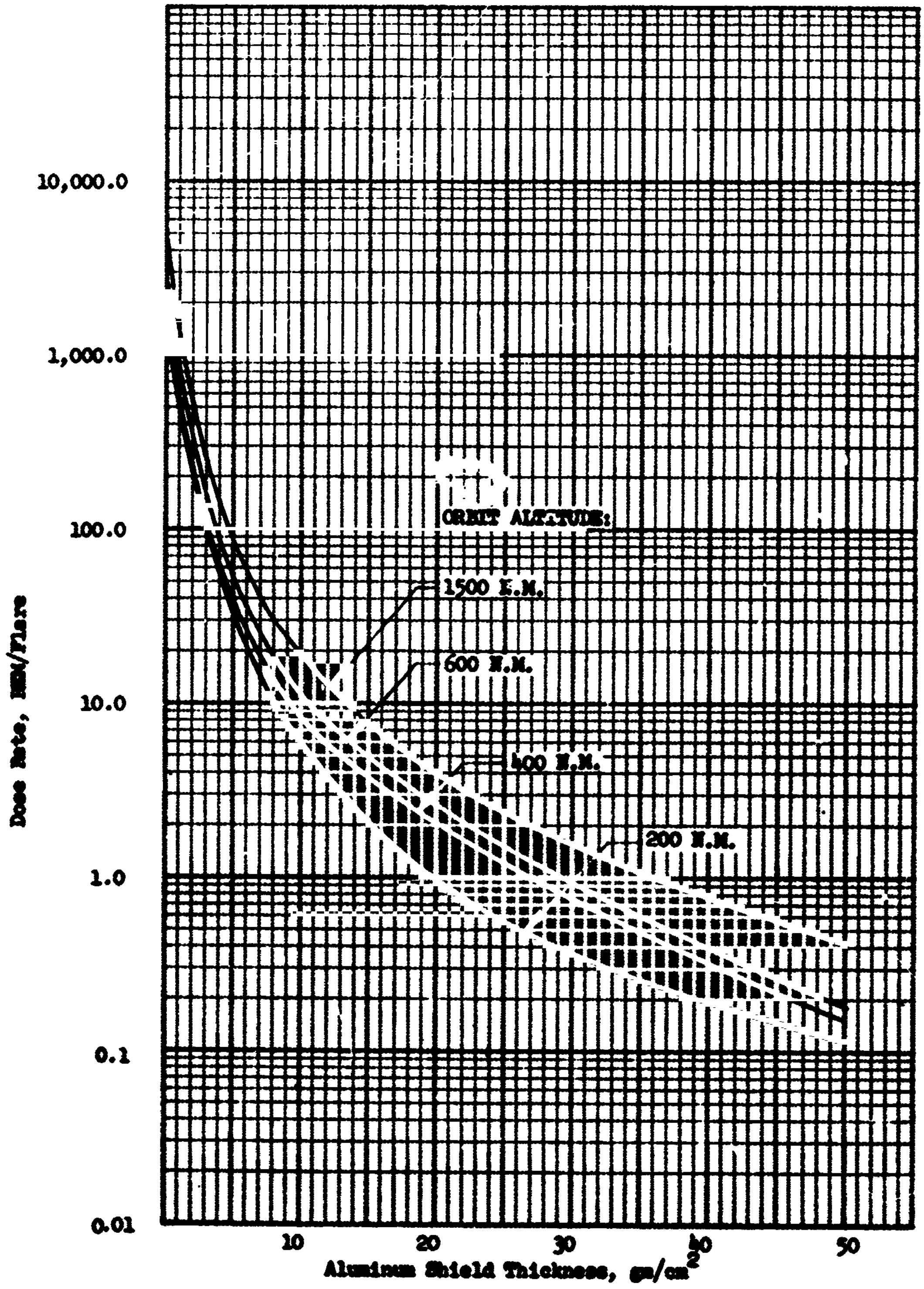


Figure 3-11. Dose Rates for Solar Flares During Earth Orbital Missions at 50° Inclination

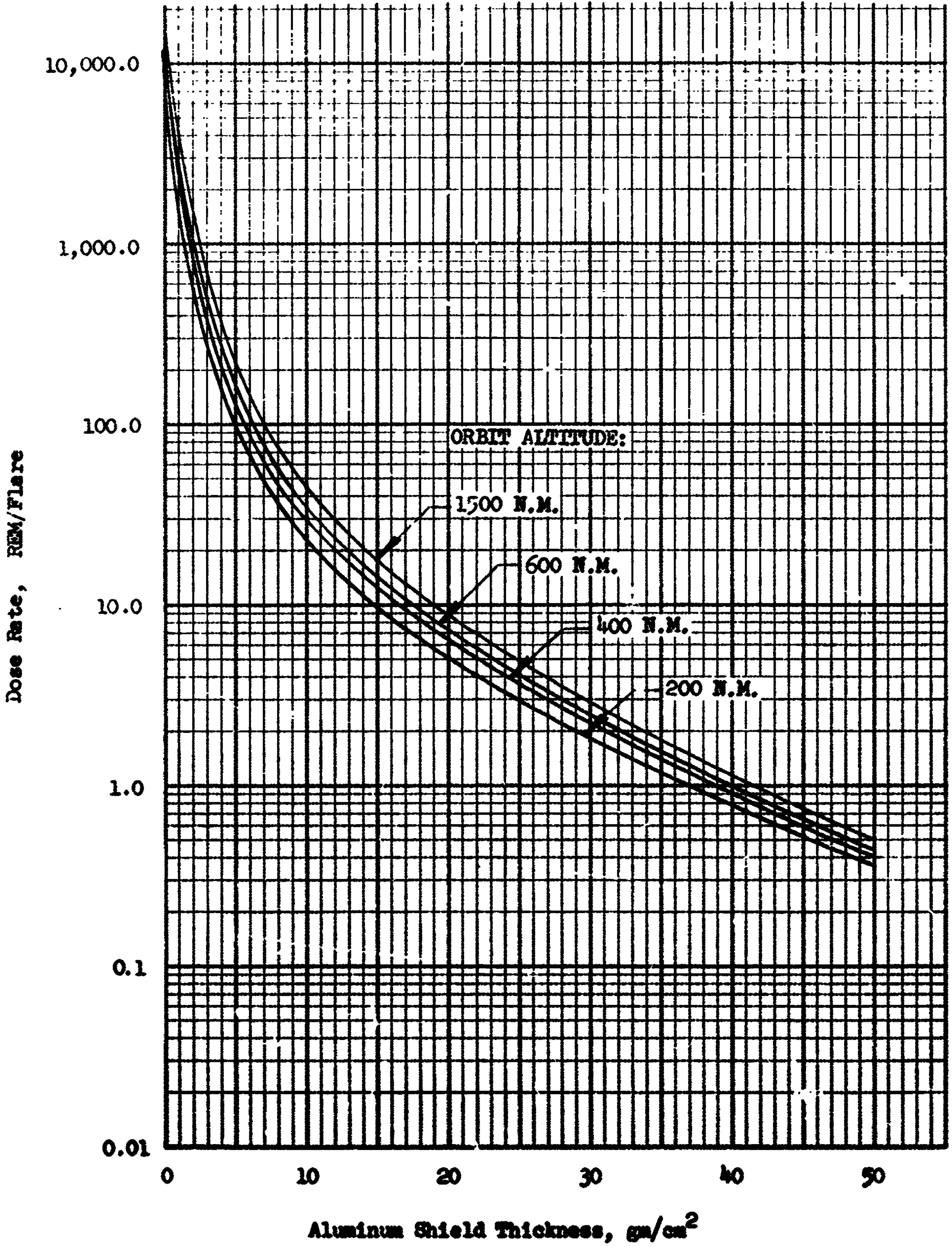


Figure 3-12. Dose Rates for Solar Flares During Earth Orbital Missions at 90° Inclination

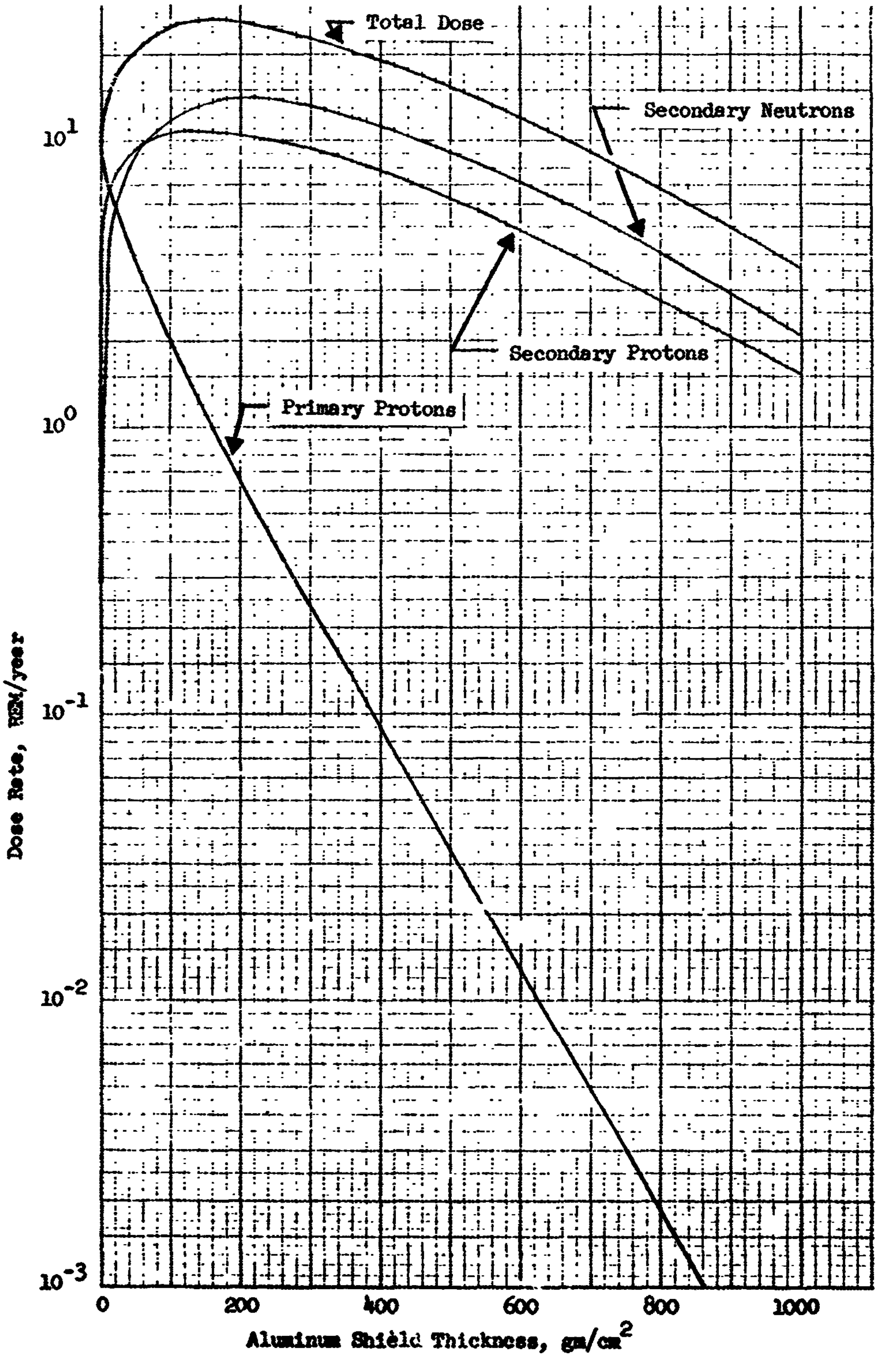


Figure 3-13. Galactic Cosmic Proton Dose

galactic cosmic rays is not practical because of the extremely high energies of these particles. Figure 3-13 shows that any probable shielding (< 100 g/cm^2 equivalent aluminum) which might be used for an interplanetary vehicle, only tends to increase the dose due to the production of secondary radiation, i.e., secondary neutrons and protons. For interplanetary vehicles with shielding equivalent to 0 to 50 g/cm^2 aluminum, the dosage would be 10 to 20 REM/year. For Earth orbiting and near Earth missions, the dose would be 5 to 10 REM/year. This is due to the interaction and attenuation by the Earth's magnetic field of these incoming stellar particles.

The galactic cosmic proton doses presented were calculated for a total free space flux of 5.7 protons/cm^2/sec incident isotropically on a spherical shield. The galactic cosmic ray proton spectrum analyzed was

$$\frac{d\phi}{dE} = 1.27 \times 10^5 (E + 1000)^{-2.4}, \text{ protons/cm}^2\text{-sec-MeV.}$$

where $10 \leq E \leq 10^5$ MeV, Reference 3-4.

Solar Cosmic Radiation

Solar cosmic rays are energetic charged particles, principally protons, emitted from the sun during solar flare activity. These particles, propagating through interplanetary space, are the greatest radiation hazard to manned missions. During the 19th solar cycle (1951 to 1961), 57 solar flare events occurred which were measured on Earth. Three flare events occurred in the 1951 to 1956 time period which is classified as the solar minimum activity period, and 54 events occurred in the 1956 to 1961 time period, classified as the active part of the solar cycle. Assuming the 19th solar cycle as typical of future solar cycles, the expected solar flare occurrence during solar maximum would be nine per year, and 0.6 per year during solar minimum.

Employing a statistical evaluation, Snyder (Reference 3-5) determined various probabilities of receiving significant radiation doses through various shield thicknesses. Figures 3-14 and 3-15 are from Reference 3-5 and present dose versus aluminum shield thickness for 1-year missions at minimum and maximum solar activity respectively. Each curve represents the indicated confidence level or probability that the mission dose will not exceed the dose shown on the curve.

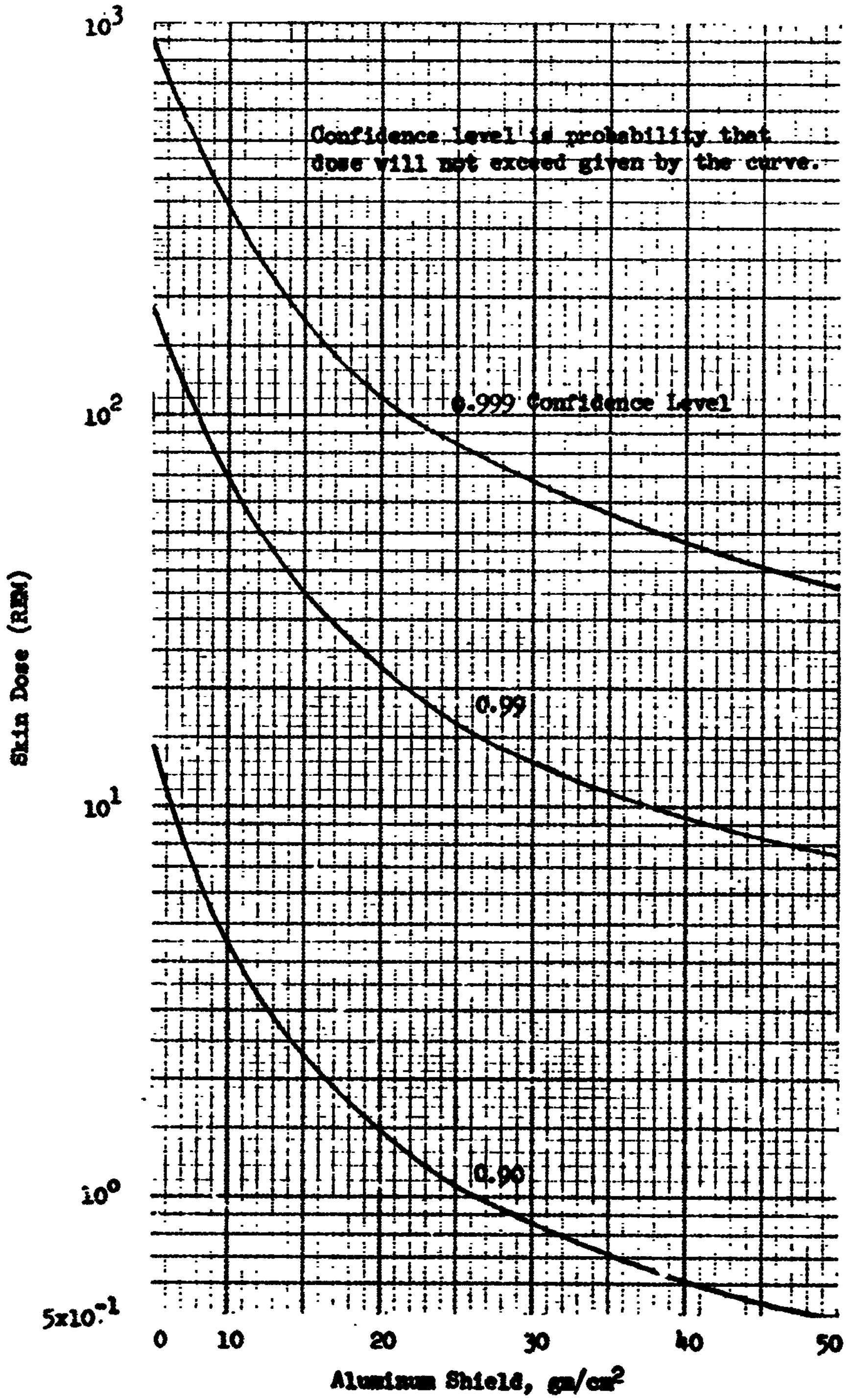


Figure 3-14. Dose vs Shield Thickness for 1-Year Missions at Solar Minimum

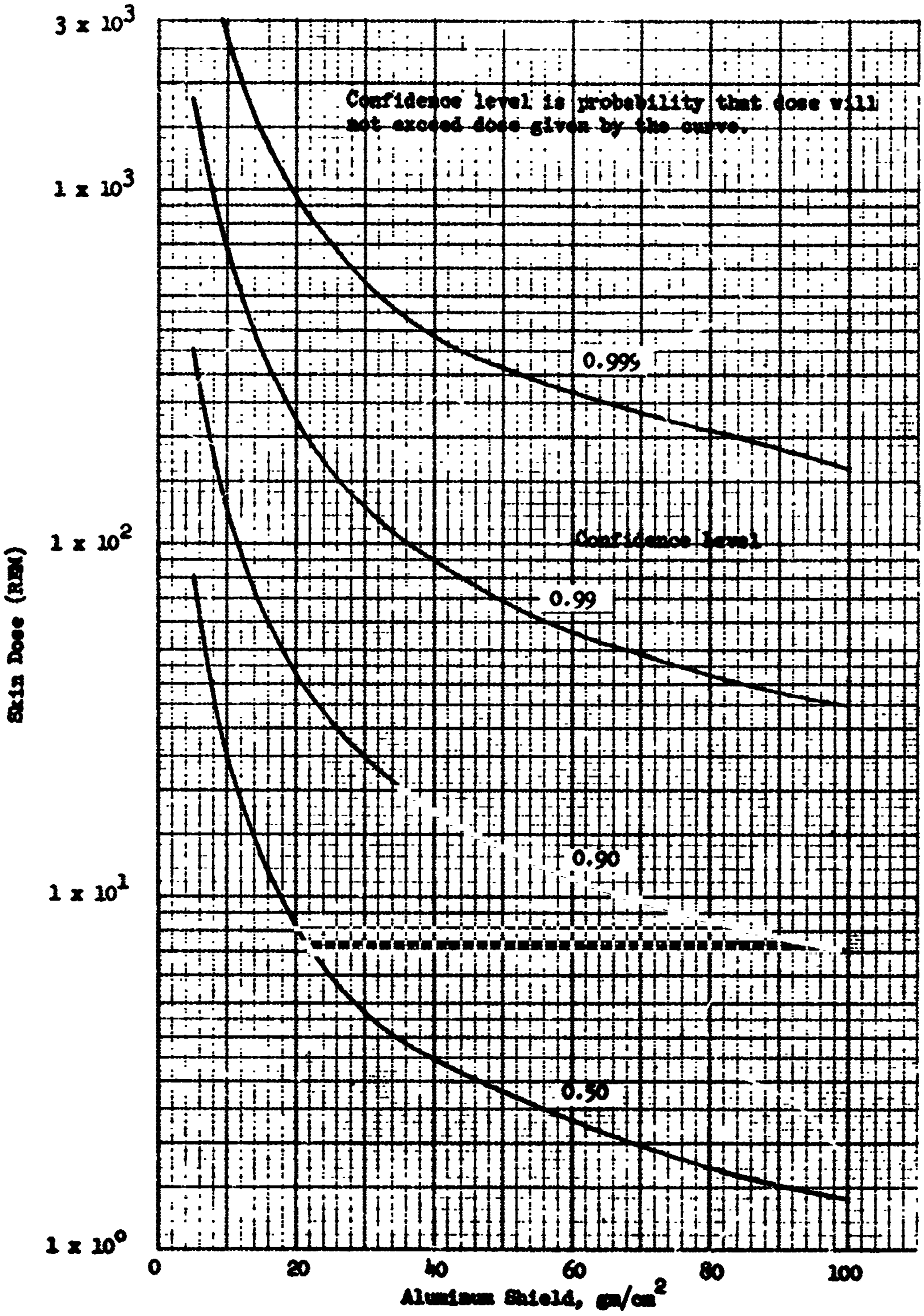


Figure 3-15. Dose vs Shield Thickness for 1-Year Missions at Solar Maximum

These data were derived by Snyder from a random sampling procedure employing 10,000 missions for each case. In each case, the number of events and a corresponding dose to be encountered on a given mission were computed. For these calculations, the frequency of proton events for solar maximum and solar minimum were taken as 0.0247 (9 per year) and 0.00164 (0.6 per year) events per day, respectively, with a binomial probability distribution for the number of events occurring during a given mission. The dose-per-event distribution used in the random sampling procedure was found to be a log-normal probability distribution. It should be noted that on Figure 3-14 no 0.50 probability curve is shown. This is because during solar minimum more than half of the missions will encounter no events. By employing a sample size such as 10,000 missions means that during solar minimum, 6,000 events and up to five events on one mission were considered. For the solar maximum case, 90,000 proton events and up to 22 events on one mission were considered.

Figure 3-16 presents the variation of dose with mission length. The data are normalized to 1.0 for a 1-year mission to facilitate use of these data in conjunction with Figures 3-14 and 3-15.

Shielding Material Effectiveness

All the dose versus shield thickness data presented considered only aluminum shielding; however, other materials may also be of interest. Figure 3-17 presents the relative proton shielding effectiveness normalized to aluminum. Using this curve, shield mass thickness (in terms of g/cm^2) for any desirable shield material can be obtained. For example, 10 g/cm^2 of aluminum is equivalent to $\frac{10}{0.63}$ g/cm^2 of lead shielding.

Storm Shelter Requirements - Interplanetary Missions

An energetic solar flare has a mean lifetime ranging from a few hours to a few days, and when compared to orbital missions of 30, 60, and 90 days or interplanetary missions of 400 to 800 days, the flare duration is small. However, in this relatively short period of time, astronauts can receive a lethal dose unless a heavily shielded section (a biowell or storm shelter) is provided. For orbital missions, if the operating procedure is to abort in the event of a flare, no biowell is needed. However, on interplanetary missions, this procedure cannot apply and a storm shelter of some type must be provided. Since some activities, i.e., operation of essential equipment, maintenance of

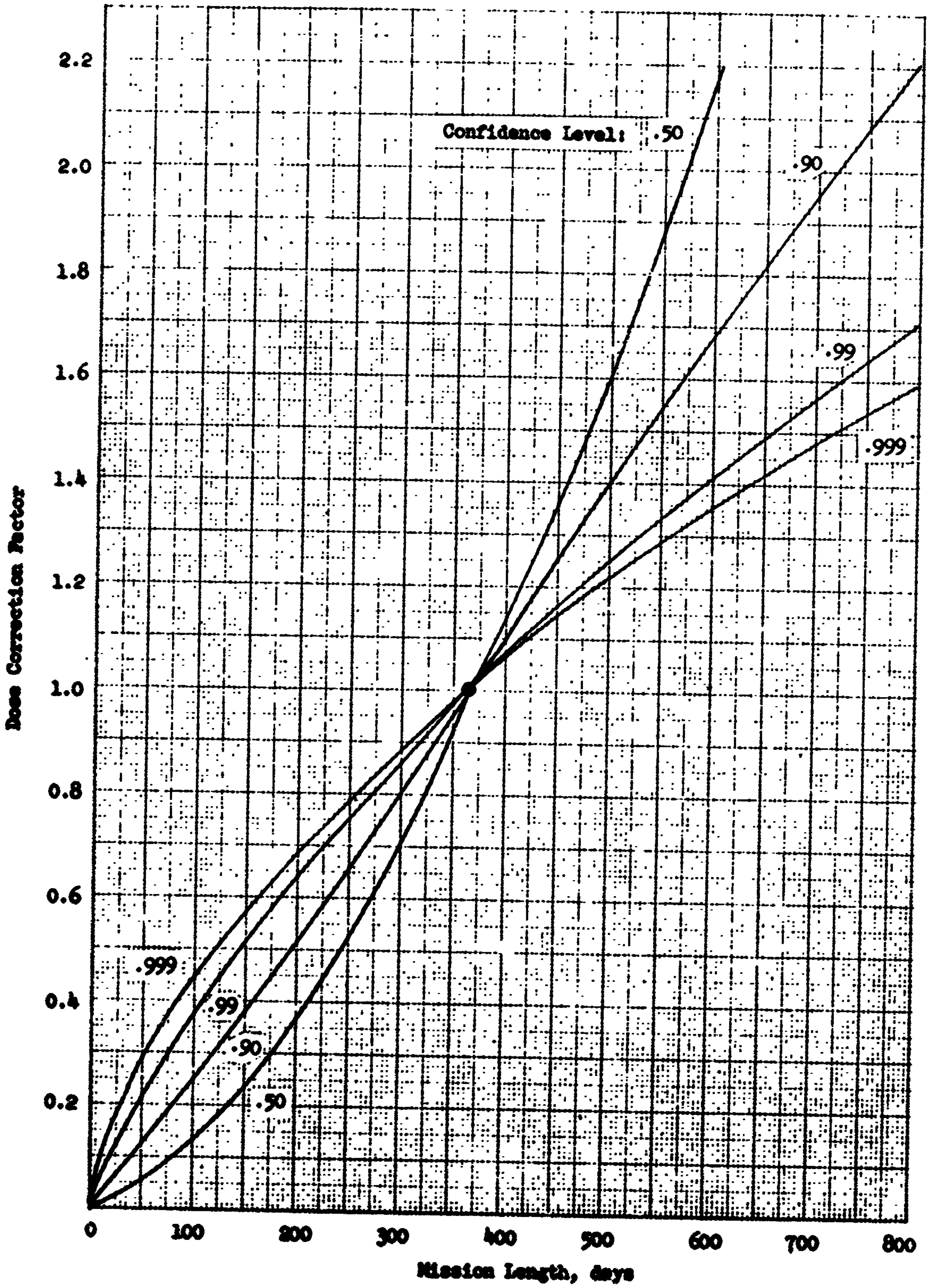


Figure 3-16. Dose Correction Factor as a Function of Mission Length

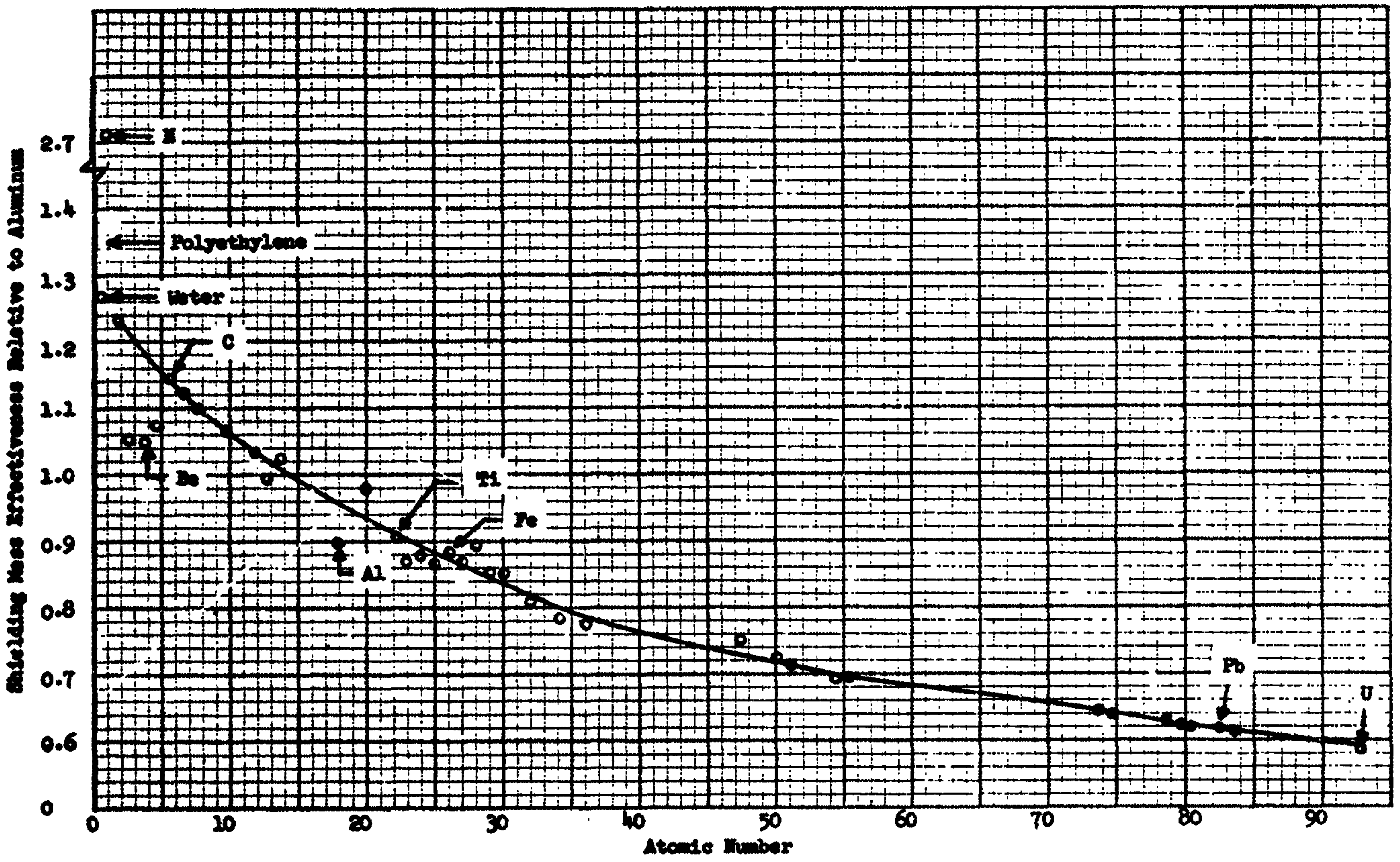


Figure 3-17. Relative Proton Shielding Effectiveness

equipment or sanitary needs may require leaving the biowell for short periods of time, the dose-time history of the best documented flare (12 November 1960) has been investigated to define the shielding design for the biowell.

Estimates of dose and dose rates for this model flare are presented in Figures 3-18 and 3-19 as a function of both shield thickness and time, as measured from solar optical maximum. These data were generated by the OGRE and CHARGE computer programs using the free-field 12 November 1960 time intensity integrals shown in Table 3-2. It is evident from the dose rate curves that going outside the heavily shielded area into a moderately shielded area (2 to 3 g/cm^2 equivalent aluminum shield) yields only 46 to 92 rad/hour, at peak intensities, which arrive at 8 to 18 hours after observing maximum intensity at the sun. Thus, short excursions lasting a few minutes would be permissible even during peak intensities. From these data, it may be assumed that the biowell design needs only to incorporate the basic essentials and have only minimum livable room.

3.2.2 Thermal Radiation

The thermal condition of a space vehicle is largely determined by the heat flowing in or out through the vehicle wall and the energy rejected by the space radiator. To evaluate these radiative heat transfer processes, the thermal environment must be known. This is determined from the orbital or interplanetary vehicle location and orientation and the outer surface radiative properties. The thermal balance at the vehicle outer surface is obtained by assuming that the heat flux to the surface, from all sources, is equal to the heat reradiated from the surface to space. Mathematically, this may be represented by the following equation:

$$\sigma \, \varepsilon_t A T_o^4 = \alpha_s A Q_s + \alpha_s A Q_a + \alpha_{ir} A Q_{ir} + Q_{net} \qquad (3\text{-}1)$$

where

σ = Stefan-Boltzmann constant
ε_t = Thermal emissivity of vehicle surface
A = Surface area of vehicle
T_o = Temperature of vehicle outer surface
α_s = Solar absorbtivity of vehicle surface
Q_s = Direct solar incident flux

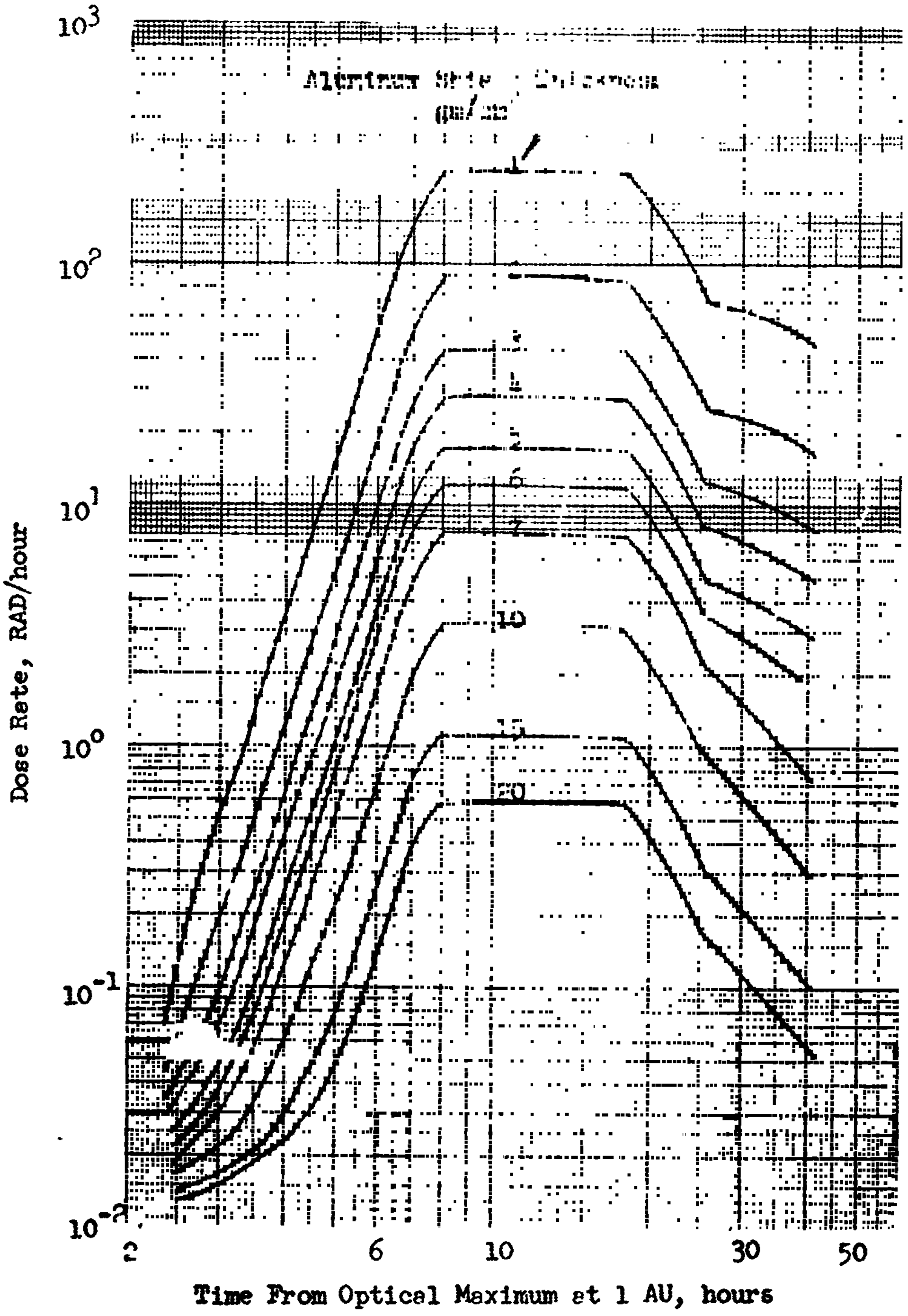


Figure 3-18. Solar Flare Dose Rate/Time History (12 November 1960)

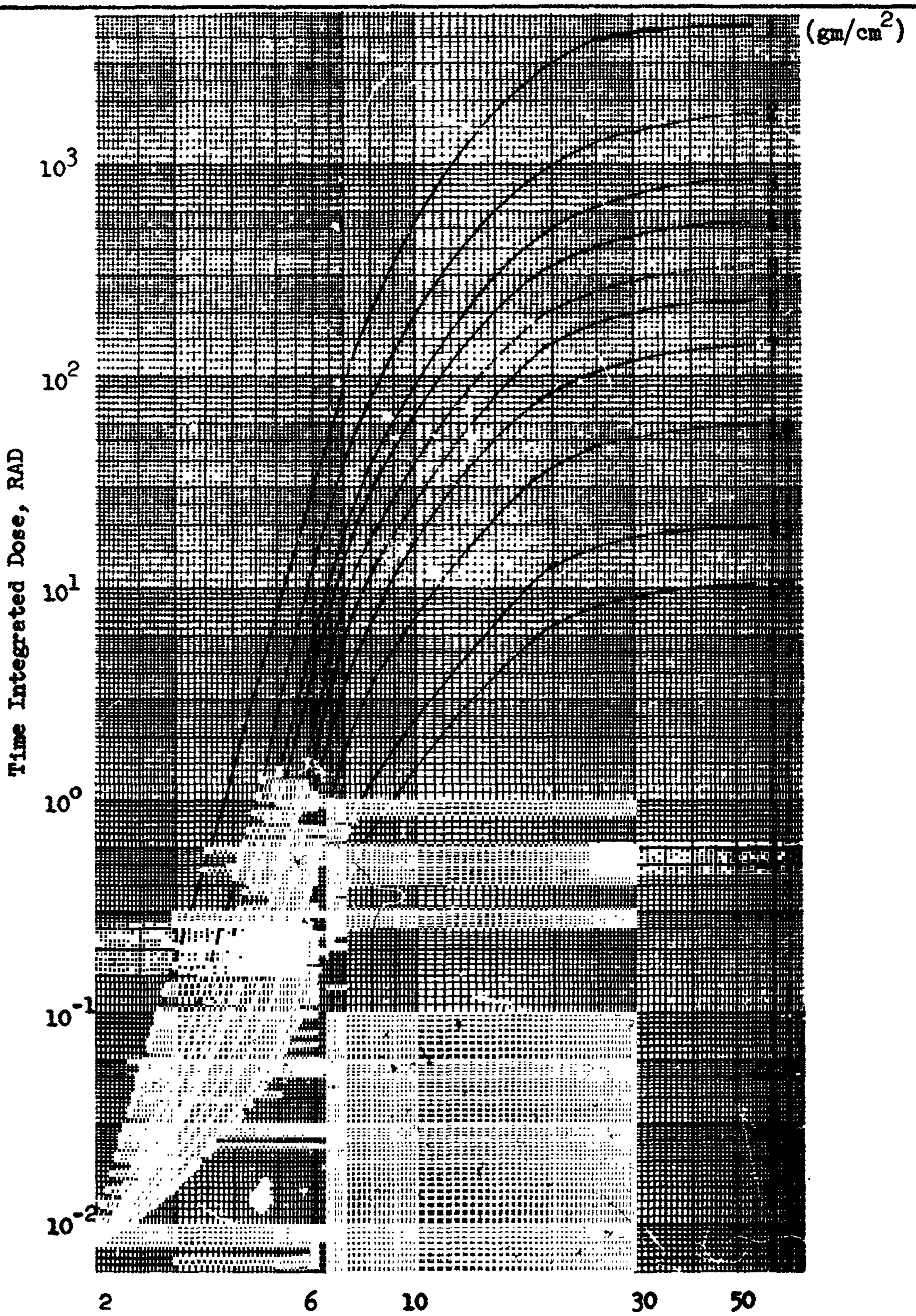


Figure 3-19. Solar Flare Integrated Dose (12 November 1960)

Table 3-2

TIME-INTENSITY HISTORY OF 12 NOVEMBER 1960 SOLAR FLARE EVENTS

Low Energy

$$\begin{aligned}\phi_L = \Bigg[& \int_{3.5}^{7.5} A T^{7}\, dT + \int_{7.5}^{18.5} B\, dT + \int_{18.5}^{26.5} C\, T^{-3.65}\, dT \\ & + \int_{26.5}^{41} D T^{-0.67}\, dT + \int_{41}^{51} E\, T^{-1/9}\, dT + \int_{51}^{56} F T^{-7}\, dT \quad \times R_L \Bigg]\end{aligned}$$

Medium Energy

$$\begin{aligned}\phi_m = \Bigg[& \int_{3.5}^{7.5} A'\, T^{7}\, dT + \int_{7.5}^{18.5} B'\, dT + \int_{18.5}^{26.5} C'\, T^{-3.65}\, dT \\ & + \int_{26.5}^{42} D'\, T^{-2.4}\, dT \Bigg] \times R_m\end{aligned}$$

High Energy

$$\phi_H = \left[\int_{0.9}^{2.1} A''\, T^{1.6}\, dT + \int_{2.1}^{7.6} B''\, dT + \int_{7.6}^{17} C''\, T^{-2.6}\, dT \right] \times R_H$$

where

$\phi_L = 8.44 \times 10^{9}$ protons/cm^2 ($30 < E < 80$ MeV)

$\phi_m = 5.87 \times 10^{8}$ protons/cm^2 ($80 < E < 440$ MeV)

$\phi_H = 3.53 \times 10^{6}$ protons/cm^2 ($440 < E < 6,600$ MeV)

and

$R_L = 4.0 \times 10^{8}$ (protons/cm^2 - hour)

$R_m = 3.3 \times 10^{7}$ (protons/cm^2 - hour)

$R_H = 4.5 \times 10^{5}$ (protons/cm^2 - hour)

Q_a = Planetary reflected solar flux (albedo) incident on vehicle
α_{ir} = Infrared absorbtivity of vehicle surface
Q_{ir} = Planetary emitted radiation incident on vehicle
Q_{net} = Heat flux supplied to the surface from within the vehicle

Equation 3-1 may be rearranged as follows:

$$\frac{Q_{net}}{A} = \sigma \varepsilon_t T_o^4 - (\alpha_s Q_s + \alpha_s Q_a + \alpha_{ir} Q_{ir}) \qquad (3\text{-}1a)$$

Equation 3-1a may also be expressed as follows:

$$\frac{Q_{net}}{A} = \sigma \varepsilon_t T_o^4 - \sigma \varepsilon_t \left\{ \frac{1}{\sigma} \left(\frac{\alpha_s}{\varepsilon_t} Q_s + \frac{\alpha_s}{\varepsilon_t} Q_a + \frac{\alpha_{ir}}{\varepsilon_t} Q_{ir} \right) \right\} \qquad (3\text{-}1b)$$

However, since the vehicle thermal emission and the planetary emitted radiation assume approximately equal wavelength distributions, the term α_{ir}/ϵ_t may be set equal to 1.0. Equation 3-1b may be rewritten as:

$$\frac{Q_{net}}{A} = \sigma \varepsilon_t T_o^4 - \sigma \varepsilon_t \left\{ \frac{1}{\sigma} \left(\frac{\alpha_s}{\varepsilon_t} Q_s + \frac{\alpha_s}{\varepsilon_t} Q_a + Q_{ir} \right) \right\} \qquad (3\text{-}1c)$$

The last term, within the braces, in Equation 3-1c may be set equal to T_s^4, thus relating net heat flux to the vehicle surface temperature and a space temperature, T_s;

$$\frac{Q_{net}}{A} = \sigma \varepsilon_t T_o^4 - \sigma \varepsilon_t T_s^4 = \sigma \varepsilon_t \left(T_o^4 - T_s^4 \right) \qquad (3\text{-}2)$$

where,

$$T_s = \left\{ \frac{1}{\sigma} \left(\frac{\alpha_s}{\varepsilon_t} Q_s + \frac{\alpha_s}{\varepsilon_t} Q_a + Q_{ir} \right) \right\}^{1/4} \qquad (3\text{-}3)$$

T_s, represents an effective environmental sink temperature, a fictitious temperature, which combines mathematically the thermal environment effects of solar heating, albedo, and planetary emitted radiation, as seen by the vehicle.

The use of an effective sink temperature eases considerably the computations involved in thermal control analyses, but the flux which it represents is dependent upon the vehicle's attitude and position in orbit.

The heat fluxes incident upon the vehicle may be expressed in terms of geometrical "view factors" relating radiative exchange between the sun, earth, planet, moon, or space and vehicle. The flux from the sun and the planetary albedo are given by:

$$Q_s = S\,F_s \tag{3-4}$$

$$Q_a = (a\,S)\,F_{sr} \tag{3-5}$$

where

S = Solar constant
F_s = View factor between sun and vehicle
F_{sr} = View factor relating sun, planet, and vehicle
a = Planet albedo

But, the portion of solar flux incident upon a planet and reradiated from the planet is dependent upon the heat balance on the planet. If incident solar flux on the projected area of the planet is set equal to the thermal radiation reflected and reradiated by the planet, then

$$S\,\pi R^2 = 4\,\pi R^2\,Q_p + (a\,S)\,\pi R^2 \tag{3-6}$$

where,

R = Planet radius
Q_p = Planet emitted radiation

then,

$$S = 4\,Q_p + a\,S \tag{3-6a}$$

or,

$$Q_p = \frac{(1-a)}{4}\,S \tag{3-6b}$$

Introducing a view factor, F_{ir}, relating radiative exchange between the planet, sun, and vehicle, then,

$$Q_{ir} = Q_p\,F_{ir} = \frac{1-a}{4}\,S\,F_{ir} \tag{3-7}$$

Employing Equations 3-4 through 3-7, Equation 3-3 may be expressed as follows:

$$T_s = \left\{\frac{1}{\sigma}\left(\frac{\alpha_s}{\varepsilon_t}\,S\,F_s + \frac{\alpha_s}{\varepsilon_t}\,a\,S\,F_{sr} + \frac{1-a}{4}\,S\,F_{ir}\right)\right\}^{1/4} \tag{3-8}$$

This relation is used in computations involving the vehicle wall insulation and space radiator sizing procedures of the thermal control subsystem. The vehicle wall's heat transfer influences the cabin heat load which in turn sizes the cabin heat exchanger and its associated equipment. Cabin walls with insulation and structure of the type selected have been found to have thermal time constants of the order of several hours during cyclic heating and cooling conditions. Sensitivity analyses of the effects of this thermal lag permit the selection of average, rather than maximum, heating conditions as being representative of the sunlit portion of orbits. This is accomplished through the use of the effective environmental sink temperature defined in Equation 3-8.

A vehicle in interplanetary flight conditions, on the other hand, may have no cyclic thermal conditions and involve time periods of many hours during which environmental thermal conditions will not significantly change. Wall heat transfer rates will then approach steady state values. Accordingly, the procedure for determining these environmental conditions is to determine the conditions for a specified distance from the sun in astronomical units (AU) and for a specified vehicle orientation to the solar vector. The thermal influence of the planets is generally insignificant compared to that of the sun during interplanetary flight and may be neglected. The solar flux (S) is a function of the distance from the sun and is given by:

$$S = 1.4\,(\mathrm{AU})^{-2}\ \mathrm{kW/m^2} \qquad (3\text{-}9)$$

The foregoing procedure for obtaining average heating conditions on a vehicle was used as the basis for a detailed study of environmental thermal conditions for a large Earth orbital space vehicle (Reference 3-6).

It was found that the results obtained in Reference 3-6 could be used or modified for orbital conditions other than those considered in the reference and also for orbital conditions at other planets. Figure 3-20 indicates the orbital geometry involved. The reference presents data for environmental heating as evaluated by a computer program for the conditions: $i = 50°$, $0° \leqq \Omega \leq 90°$, and $-23.50 \leqq \delta \leqq +23.5°$. These conditions cover much of the range of desired orbits for this study. The statistically averaged heating conditions for the sunlit portions of Earth orbits at 309 km altitude give an average sink temperature of 230°K. The results are based on an albedo of 0.35 and an α_s/ϵ_t value of 0.193.

Ω - Right ascension of ascending node

δ - Declination of sun

i - Inclination of orbit plane

β - Angular distance from equator

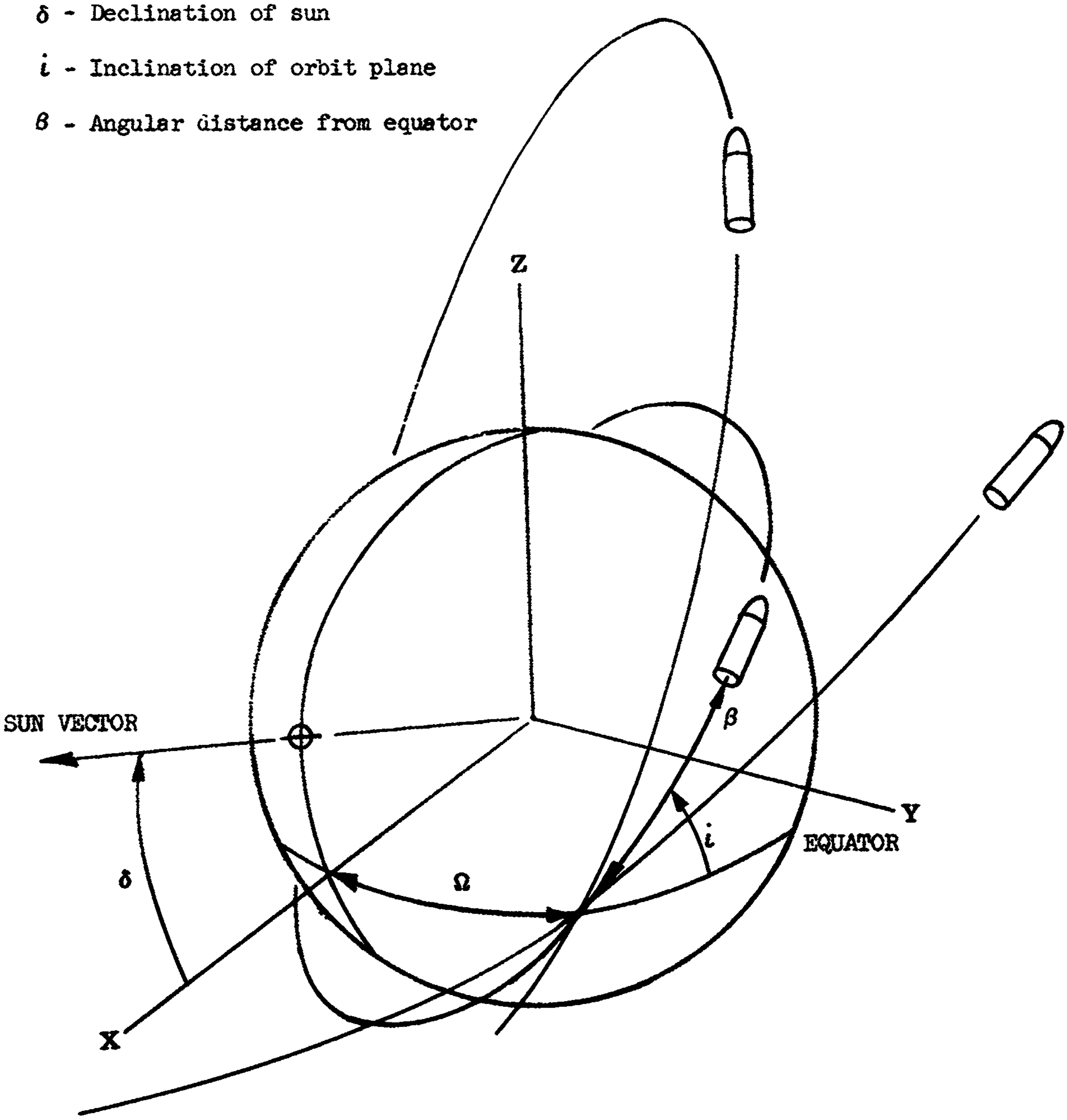


Figure 3-20. Orbital and Flyby Geometry

The 230°K sink temperature in the notation of Equation 3-8, corresponds to the following:

$$\text{Solar:}\quad S\,\overline{F}_s = 0.332\ \text{kW/m}^2 \qquad (3\text{-}9a)$$

$$\text{Albedo:}\quad aS\,\overline{F}_{sr} = 0.065\ \text{kW/m}^2 \qquad (3\text{-}9b)$$

$$\text{Planetary emitted radiation:}\quad \frac{1-a}{4}\,S\,\overline{F}_{ir} = 0.085\ \text{kW/m}^2 \qquad (3\text{-}9c)$$

$\overline{F}_s$, $\overline{F}_{sr}$, and $\overline{F}_{ir}$ denote reference view factors which are used in the computations for determining cabin wall heat transfer characteristics. The sink temperature selected as a reference temperature was $T_{s,ref} = 230°K$. This referenced temperature may then be used to determine the effective sink temperature, T_s, for other flight altitudes, and α_s/ϵ_t ratios for Earth orbits. In the case of other planets, it may also be used for determining T_s for various flight altitudes, α_s/ϵ_t ratios and albedos. The reference view factors $\overline{F}_s$, $\overline{F}_{sr}$, and $\overline{F}_{ir}$ are averaged over the vehicle and the orbital paths. For this condition, the solar radiation view factor from Equation 3-9a is found to be $\overline{F}_s = 0.237$ at 1 AU and a solar flux of 1.400 kW/m^2. A more general expression for the solar radiation view factor for a cylindrical vehicle is given by:

$$F_s = \frac{1}{\pi}\cos\gamma \qquad (3\text{-}9d)$$

where: γ is the angle between the solar vector and a plane normal to the vehicle longitudinal axis.

The values for $\overline{F}_s$ and for F_s at $\Omega = 0$ and $\beta = 45°$ are shown in Table 3-3.

The albedo view factor F_{sr} is a function of vehicle orientation, defined by angles δ, Ω, β, and i in Figure 3-20 and the ratio of flight altitude to planet radius $\frac{H}{R}$. The reference value for $\overline{F}_{sr}$ is 1.33 (Equation 3-9b). Values of F_{sr} for a cylindrical vehicle with $\Omega = 0$, and linearly averaged for $-90° \leq \beta \leq +90°$, over a wide range of $\frac{H}{R}$ values are shown in Table 3-3. For values of $\frac{H}{R}$ different from $\frac{H}{R} = 0.0476$, (reference case), the selected values of $\overline{F}_{sr}$ were obtained by maintaining a constant ratio between F_{sr} ($\Omega = 0$) and $\overline{F}_{sr}$. The view factor for planetary emitted radiation is independent of vehicle orientation with respect to the solar vector and is a function of $\frac{H}{R}$ only. Values of F_{ir} are shown in Table 3-3.

Table 3-3

VIEW FACTORS FOR CYLINDER WITH LINE OF FLIGHT ORIENTATION

$\frac{H}{R}$	$\delta = 0$ $\beta = 45^\circ$ $\Omega = 0^\circ$ F_s	$\bar{F}_s$	$\delta = 0$ $\Omega = 0$ linear average for $-90^\circ \leqq \beta \leqq +90^\circ$ F_{sr}	$\bar{F}_{sr}$	$F_{ir} = \bar{F}_{ir}$
0.029	0.225	0.237	0.238	0.141	0.402
0.0476(1)	--	--	0.225	0.133	--
0.174	0.225	0.237	0.155	0.0915	0.27
0.29	0.225	0.237	0.121	0.0715	0.214
1.76	0.225	0.237	0.0212	0.0125	0.0431
2.90	0.225	0.237	0.0098	0.0058	0.021

NOTES:

1. Reference case for Earth orbital cylindrical vehicle from Reference 3-7.
2. $\frac{H}{R} = \frac{\text{flight altitude}}{\text{planet radius}}$
3. F_{sr} and F_{ir} data from Reference 3-8.
4. F_s and F_{sr} data based on reference case for $\frac{H}{R} = 0.0476$ and modified as required for other $\frac{H}{R}$ values.
5. Angles δ, β, and Ω are identified on Figure 3-20.

Reference values of planet radius, albedo, and distance from the sun considered in this study are shown in Table 3-4. In the case of orbital flight conditions, flight altitude and α_s/ε_t values must be specified and the data in Tables 3-3 and 3-4 are used in Equation 3-8 to determine the average vehicle sink temperature. Interplanetary flight conditions require only the solar radiation term in Equation 3-8 to determine T_s. Equation 3-9d is used to obtain the solar view factor for these cases. View factors for other spatial locations and orientations than shown above are given in Reference 3-9.

Table 3-4

PLANETARY DATA REQUIRED FOR THERMAL ANALYSES

Planet	Radius (km)	Albedo	Sun Distance (AU)
Earth	6,380	0.35	1.0
Moon	3,480	0.07	1.0
Mars	3,340	0.15	1.52
Venus	6,040	0.61	0.725
Mercury	2,500	0.06	0.384
Jupiter	69,500	0.41	5.2

3.2.3 Meteoroid Flux and Penetration Criteria

This section presents the mathematical relations used for estimating the meteoroid fluxes, penetration criteria and shielding requirements. The criteria used in the analysis are from Savin in Reference 3-10.

The flux criteria are as follows:

Flux Model

Cometary (1963 Whipple Model)

$$\log \phi_c = -14.44 - 1.34 \log m \tag{3-10}$$

Nominal Asteroidal

$$\log \phi_{a,\,nom} = -17.34 + 3.53r - 0.63r^2 - 0.80 \log m \tag{3-11}$$

Maximum Asteroidal

$$\log \phi_{a,\,max} = -21.17 + 8.19r - 1.46r^2 - 0.93 \log m \tag{3-12}$$

where

ϕ = No. of particles/m^2 sec

m = Particle mass, g

r = Heliocentric distance, AU

Additional meteoroid characteristics are assumed to be:

ρ_p = particle density
= 0.5 g/cc cometary
= 3.5 g/cc asteroidal

V = impact velocity
= $30\ r^{-1/2}$ km/sec, cometary (isotropic)
= $15\ r^{-1/2}$ km/sec, asteroidal (unidirectional)

The asteroidal flux is assumed to peak at the center of the asteroid belt at 2.8 AU. The size/frequency distribution data for meteoroids in the asteroid belt from Reference 3-11 were used to obtain estimates of maximum and nominal fluxes.

Penetration Models

$$\frac{\Delta}{d} = 1.64\, k_1 \left(\frac{\rho_p}{\rho_t}\right)^{1/2} \left(\frac{V}{c}\right)^{2/3} d^{1/18} \qquad (3\text{-}13)$$

where

$\frac{\Delta}{d}$ = penetration depth to particle diameter ratio, dimensionless
d = particle diameter, cm (spherical particle assumed)
ρ_t = target density, g/cc
c = speed of sound in target, km/sec
k_1 = factor determining completeness of penetration
= 1.5 to just prevent penetration

Equation 3-13 can be rewritten in terms of particle mass as follows:

$$m = \frac{1}{6}\pi d^3 \rho_p$$

$$d = \left(\frac{6m}{\pi \rho_p}\right)^{1/3} \qquad (3\text{-}14)$$

then,

$$\frac{\Delta}{d} = \frac{\Delta}{\left(\frac{6m}{\pi\rho_p}\right)^{1/3}} = 1.64\, k_1 \left(\frac{\rho_p}{\rho_t}\right)^{1/2} \left(\frac{V}{c}\right)^{2/3} \left(\frac{6m}{\pi\rho_p}\right)^{1/54}$$

and,

$$m = \frac{\pi\rho_p}{6} \left(\frac{\Delta}{1.64\, k_1 \left(\frac{\rho_p}{\rho_t}\right)^{1/2} \left(\frac{V}{c}\right)^{2/3}} \right)^{\frac{54}{19}} \qquad (3\text{-}15)$$

It is well known that the use of multiple sheets for meteoroid shielding can improve the efficiency of meteoroid protection. Increasing the sheet spacing and reducing the density of the absorbing material further improves this efficiency. Since these effects have not been completely formulated as yet, the relatively conservative approach from Reference 3-12 is adopted, as suggested in Reference 3-13.

$\bar{t}$ = $K_2 \Delta$
$\bar{t}$ = total thickness of double sheet
K_2 = efficiency factor, varies between 0.2 and 0.5
K_2 = 0.3 is used in the computational logic

Meteoroid shielding requirements for the walls of manned compartments and for the tubes of space radiator assemblies can be determined for the space missions specified for this study (see Section 3.1.1). Independent variables considered in this regard will be target area and probabilities of various numbers of penetrations. Probabilities of no penetration will be used for determining shielding requirements for manned compartment walls, and probabilities of one penetration will be used in determining shielding requirements for space radiator tubes. A redundant set of tubes is used in the radiator model. A future study project is consideration of various numbers of penetrations for radiator tubes in trading off shielding weights against weight for redundant sets of radiator tubes. Due to the isotropic nature of cometary flux, total exposed areas are appropriate for use in evaluating the corresponding shielding requirements.

Asteroidal flux, however, is considered to have a predictable direction. Therefore, projected side view areas of manned compartments and space radiator supporting structure will be used in determining shielding requirements. Required shielding thicknesses will be assumed to be applied to entire surface areas for manned compartments. In the case of space radiators, the shielding will be assumed to cover the tubing with material three tube diameters wide. In the event that assumptions concerning shielding areas different than those used in this study are required, the study results will be easily adapted to these new assumptions.

The usual assumption of the Poisson distribution for describing the probabilities of meteoroid penetration is adopted:

$$p(x) = \frac{e^{-\lambda}\lambda^{x}}{x} \qquad x = 0,\ 1,\ 2, \tag{3-16}$$

x = number of penetrations
λ = integral of meteoroid flux for space mission
$= \int_T (\phi_c + \phi_a)\, A\, dt$

From Equations 3-10, 3-11, and 3-12 the flux is a function of particle mass and heliocentric distance. But of these only heliocentric distance is assumed to be a function of time. Heliocentric distance is related to time for particular space missions. Particle mass is related to shielding thickness through Equation 3-15. The above functional relationships are expressed as follows:

$$\phi_c + \phi_a = \frac{F_r(r)}{F_\Delta(\Delta)}$$

$$= \frac{F_t(t)}{F_\Delta(\Delta)} \tag{3-17}$$

$$\lambda = \int_T \frac{F_t(t)\, A\, dt}{F_\Delta(\Delta)} \tag{3-18}$$

For a given mission, the integral in the above expression for λ is determined. Various combinations of probability, target area, and shield thickness can be determined from Equation 3-16.

3.3 CREW DATA

Crew data include the information about the crew members required to provide the basis for establishing vehicle and subsystem requirements in support of the crew. It is necessary to consider these items in the design of the life support system to ensure unimpaired crew performance. The physiological and psychological well being of the crew must be maintained for a successful mission. The crew data considered are primarily of a physical nature; however, some crew psychological aspects are considered later in the crew accommodation facilities. The crew data considered are discussed in the following order:

1. Crew time available for mission durations of 30 days to 3 years.
2. Crew physical criteria for a 20 to 95 percentile range.
3. Crew metabolic and physiological data.
4. Comfort criteria.

3.3.1 Crew Time Available

The three types of crew duties and responsibilities examined in order to assess and evaluate the manned support requirement of spacecraft are: operations, personal duties and maintenance. The spacecraft operations are characterized by the vehicle and crew demands and by mission objectives and include space biological or physical science experiments, planetary explorations, or military operations. Personal duties and functions include eating and food preparation, mental and personal hygiene, exercise and health maintenance, sleep, rest and recreation. Maintenance duties include subsystem operation and regular repair, housekeeping and any emergency or repair functions. Reference 3-14 has been used as a basis to define scheduled and unscheduled maintenance time requirements. These criteria are shown in Figure 3-21.

The time available for spacecraft operations is the difference between total daily crew time and that time required for maintenance functions and personal

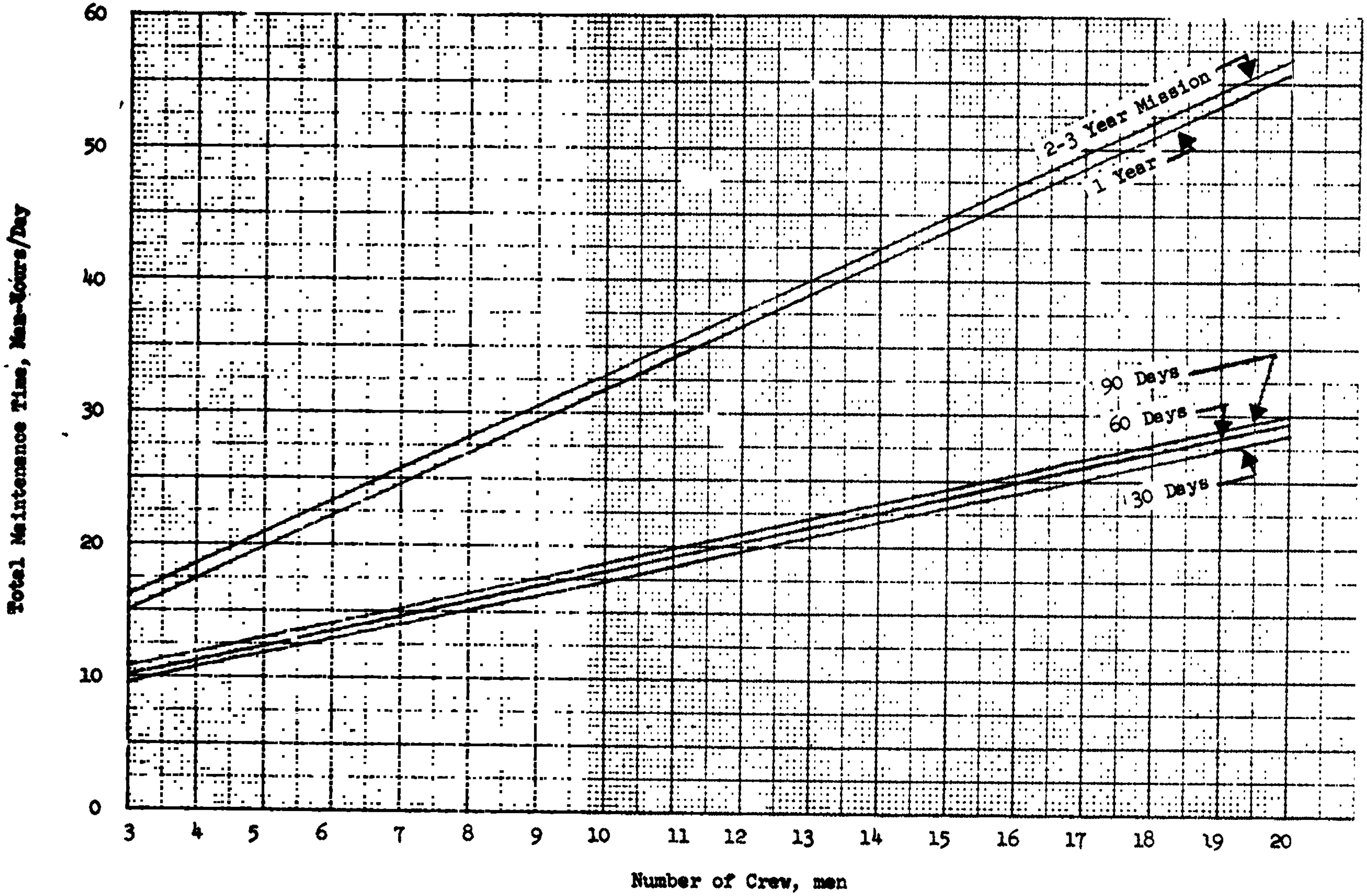


Figure 3-21. Total Estimated Maintenance Time Requirements

duties. This estimated time is plotted in Figure 3-22. For missions with less than 30-day durations, the crew members are usually capable of sustaining higher work loads and requiring less sleep and fewer rest periods, and therefore, the crew sizes will be primarily determined by the operational purposes of the mission. For longer duration missions, maintenance needs will become an important criterion and a major consideration in determining crew sizes.

3.3.2 Crew Physical Characteristics

The range of crew body weights and pertinent physical dimensions are presented in Table 3-5 for the specified range of 20 to 95 percentile of the United States Air Force flying personnel (Reference 3-15). The corresponding dimensions for personnel in soft type space suits are included in this table, and these are based on data obtained from the MC-2 full pressure suits.

The total body surface area is another physical characteristic of interest. It may be expressed in terms of height and weight as follows:

$$A = 0.00718\, W^{0.425}\, H^{0.725} \qquad (3\text{-}19)$$

where

A = surface area, in.^2
W = weight, kg
H = height, cm

But for heat balance considerations, the radiation area of the body varies with body position. A radiation area factor (f_r) is used to modify Equation 3-19 to obtain the effective radiation area, A_r, for several body postures.

Thus,

$$A_r = 0.00718\, f_r\, W^{0.425}\, H^{0.725} \qquad (3\text{-}20)$$

where,

f_r = 0.65 for a crouched position
= 0.7 for a seated position
= 0.77 for a standing position

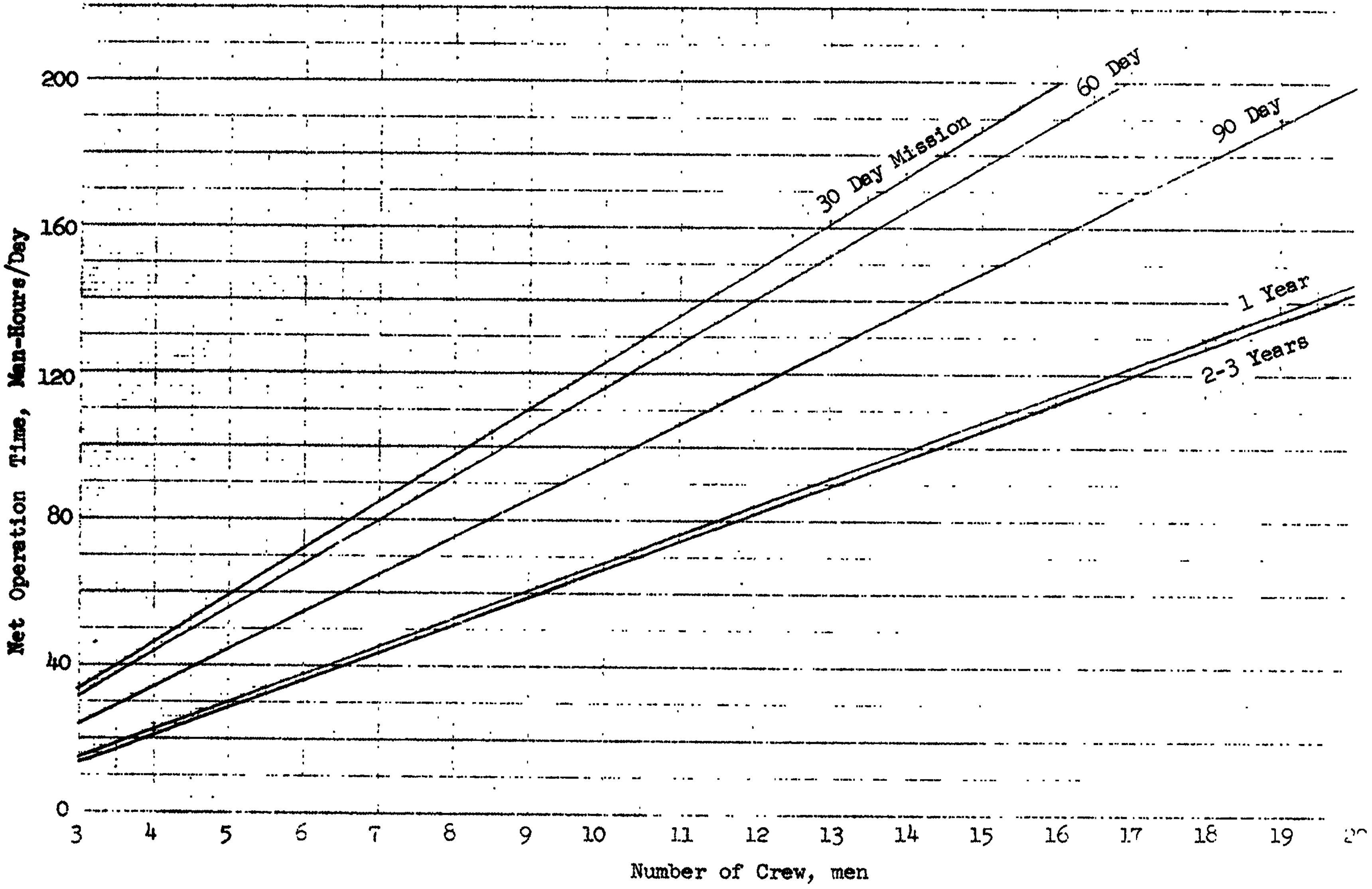


Figure 3-22. Time Available for Space Operations

Table 3-5

CREW PHYSICAL CHARACTERISTICS

Percentile Body Size	20	40	60	80	95	Multiplying Factor for Space Suits
Weight, kg	66.2	71.2	75.7	79.8	89.4	----
(lb)	(146)	(157)	(167)	(176)	(197)	
Standing height, cm	171.5	174	178	183	186.5	1.08
(in.)	(67.5)	(68.5)	(70)	(72)	(73.5)	(1.08)
Shoulder height, cm	137.2	142.2	144.8	148.5	153.3	1.035
(in.)	(54)	(56)	(57)	(58.5)	(60.5)	(1.035)
Crotch height, cm	77.5	80	82.6	85	87.7	0.97
(in.)	(30.5)	(31.5)	(32.5)	(33.5)	(34.5)	(0.97)
Sitting height, cm	89	91.5	94	95.2	97.7	1.03
(in.)	(35)	(36)	(37)	(37.5)	(38.5)	(1.03)
Knee height-sitting, cm	52.2	53.3	54.7	57.2	59.7	1.09
(in.)	(20.5)	(21)	(21.5)	(22.5)	(23.5)	(1.09)

3.3.3 Crew Metabolic and Physiological Data

Basically, life support in the closed environment of space vehicles is concerned with balancing the metabolic processes of the crewmen. Thus, the energy expended by the body must be normally replenished by the energy supplied in the food and oxygen. Involved in this energy conversion process is potential energy available in the food, the process water, and the waste products.

3.3.3.1 Food

As diet is a mixture of carbohydrates, fat, and protein, the metabolic reactions can be calculated from the individual constitutents of the diet. For example, the reaction for glucose, which is one form of carbohydrate, may be written as follows:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{Energy (4.1 kcal/g of carbohydrates)} \qquad (3\text{-}21)$$

Also, the reaction for diet fat such as tristearin is,

$$2\ C_{57}H_{110}O_6 + 163\ O_2 \rightarrow 114\ CO_2 + 110\ H_2O + \text{Energy (9.5 kcal/g of fat)} \qquad (3\text{-}22)$$

No simple relations can be expressed for proteins due to the complexity of protein molecules; however, the accepted value of energy generated from the diet protein reaction is approximately 4.3 kcal/g of protein. The relation between the food consumed and the energy, H, generated may thus be given by the relation:

$$H \text{ (in kilocalories)} = 4.1W_c + 9.5W_f + 4.3W_p \qquad (3\text{-}23)$$

where W_c is the carbohydrate weight in grams, W_f is the fat weight in grams, and W_p the protein weight in grams.

Adequate human daily diets normally provide 2,000 to 3,000 kcal in the proportion of 5 to 15% protein, 15 to 40% fats, and 50 to 70% carbohydrates. The recommended minimum daily requirements of protein to provide the necessary "indispensable" amino acids, or those which cannot be synthesized from other constituents in the ordinary diets, varies between 15 and 65 g/day for healthy active adults. This corresponds to a value of slightly less than 1.0 g for each kilogram of body weight. The protein intake value to be used in this report will be 1.0 gram per kilogram of body weight and this is the same value recommended by the Food and Nutrition Board of the National Research Council. Thus, for a body weight of W_b in kilograms, Equation 3-23 may be rewritten as:

$$H(\text{in kilocalories}) = 4.1\ W_c + 9.5\ W_f + 4.3\ W_b \qquad (3\text{-}24)$$

The ratio of fat to carbohydrates, the fat ratio (FR), in diets will be varied within some range to determine the effect the diet on the sensitivity of life support systems to various diets. A fat ratio of 0.3 is the minimum requirement for a normal active person.

3.3.3.2 Oxygen

Carbohydrates contain hydrogen and oxygen in about the same proportion as is found in water. Thus, when these substances oxidize, the volume of carbon dioxide formed is approximately equal to the volume of oxygen utilized. The ratio of the volume of carbon dioxide formed to the volume of oxygen absorbed is known as the respiratory quotient (RQ). The respiratory quotients from Equations 3-21 and 3-22 are 1.0 for carbohydrates and 0.705 for fats. The reaction equation for protein is not easily defined but the average oxidation of meat protein may be given by the following relation:

$$\begin{aligned}&100\ \text{g of meat protein} + 138.18\ \text{g}\ O_2 \rightarrow 152.17\ \text{g}\ CO_2\\&+ 39.602\ \text{g}\ H_2O + \text{miscellaneous compounds} \qquad (3\text{-}25)\end{aligned}$$

This gives an RQ for protein of 0.8 which will be used in this study.

Based on the above, the relations for the intake of O_2 and the generation of CO_2 and the metabolic water may be expressed as follows:

$$\text{Oxygen Consumption (in liters at STP)} = 0.75\ W_c + 2.05\ W_f + 0.97\ W_p \qquad (3\text{-}26)$$

$$CO_2\ \text{Production (in liters at STP)} = 0.75\ W_c + 1.43\ W_f + 0.78\ W_p \qquad (3\text{-}27)$$

$$\text{Metabolic Water Production (in g)} = 0.6\ W_c + 1.06\ W_f + 0.40\ W_p \qquad (3\text{-}28)$$

Equations 3-26 through 3-28 are based on 100% utilization of food to produce heat energy. To allow for the inefficiencies in human processes, and relating protein to body weight, the equations become:

$$\text{Oxygen Consumption (in liters at STP)} = 0.83\ W_c + 2.05\ W_f + 0.97\ W_b \qquad (3\text{-}29)$$

$$CO_2 \text{ Production (in liters at STP)} = 0.83\ W_c + 1.43\ W_f + 0.78\ W_b \qquad (3\text{-}30)$$

$$\text{Metabolic Water Production (in grams)} = 0.55\ W_c + 1.06\ W_f + 0.4\ W_b \qquad (3\text{-}31)$$

3.3.3.3 Water

Human process water intake, either as drinking water or in food, averages per day about 1.0 g for each kilocalorie of food consumed. This value will be used in this study and the dietary water requirements are given in the following relation:

$$\text{Water Intake (in grams)} = 4.1\ W_c + 9.5\ W_f + 4.3\ W_b \qquad (3\text{-}32)$$

Body water output is equivalent to the sum of water intake and metabolic water and is given by the following equation:

$$\text{Total water output (in grams)} = 4.66\ W_c + 10.57\ W_f + 4.7\ W_b \qquad (3\text{-}33)$$

This total water output may be divided into urine, respiration, perspiration and fecal water as follows:

$$\text{Urine (in grams)} = 2.62\ W_c + 5.93\ W_f + 2.65\ W_b \qquad (3\text{-}34)$$

$$\text{Respiration (in grams)} = 0.93\ W_c + 2.12\ W_f + 0.94\ W_b \qquad (3\text{-}35)$$

$$\text{Perspiration (in grams)} = 0.93\ W_c + 2.12\ W_f + 0.94\ W_b \qquad (3\text{-}36)$$

$$\text{Fecal Water (in grams)} = 0.18\ W_c + 0.39\ W_f + 0.17\ W_b \qquad (3\text{-}37)$$

3.3.3.4 Metabolic Residue

In addition to the essential dietary food and water requirements, an amount of indigestible bulk is considered essential for normal nutrition and elimination processes. The quantity of indigestible bulk varies considerably with diets, and, in turn, affects the amount of fecal residues processed. Food types are usually ranked in increasing order of fecal residue production as follows: protein, fats, digestible carbohydrates and carbohydrates with indigestible material. The quantity of indigestible bulk in foodstuffs may be given by the following equation:

$$\text{Indigestible Bulk (in grams)} = 0.15\ W_c + 0.34\ W_f + 0.15\ W_b \qquad (3\text{-}38)$$

Solids excreted by the body are classified as urinary solids, fecal solids, and skin and other solids. Urinary solids may be given as follows:

$$\text{Urinary Solids (in grams)} = 0.12\ W_c + 0.27\ W_f + 0.12\ W_b \qquad (3\text{-}39)$$

Fecal excretion includes an average water content of 72%.

$$\text{Fecal Solids (in grams)} = 0.07\ W_c + 0.16\ W_f + 0.07\ W_b \qquad (3\text{-}40)$$

The quantities of skin, nails, and other solids are given by the following relation:

$$\text{Skin and Other Solid Excretions (in grams)} = 0.06\ W_c + 0.14\ W_f + 0.07\ W_b$$

Figures 3-23 through 3-25 have been plotted using the relations derived in this paragraph and show the interdependencies between food consumption, fat ratio, metabolic rate, oxygen consumption, and CO_2 and water output.

When considering a range of crew body sizes, it is convenient to use basal metabolic rate (BMR) as a basis for determining the metabolic rates. Numerous attempts have been made to correlate BMR with body dimensions and the most successful correlation is based on body unit surface area. The BMR for adult males between 20 and 40 years of age is found to be about 39.5 Kcal/m^2 hr. Upon substituting this value in Equation 3-19 one obtains:

$$\text{BMR (in Kilocalories per hour)} = 0.28\ W^{0.425}\ H^{0.725} \qquad (3\text{-}42)$$

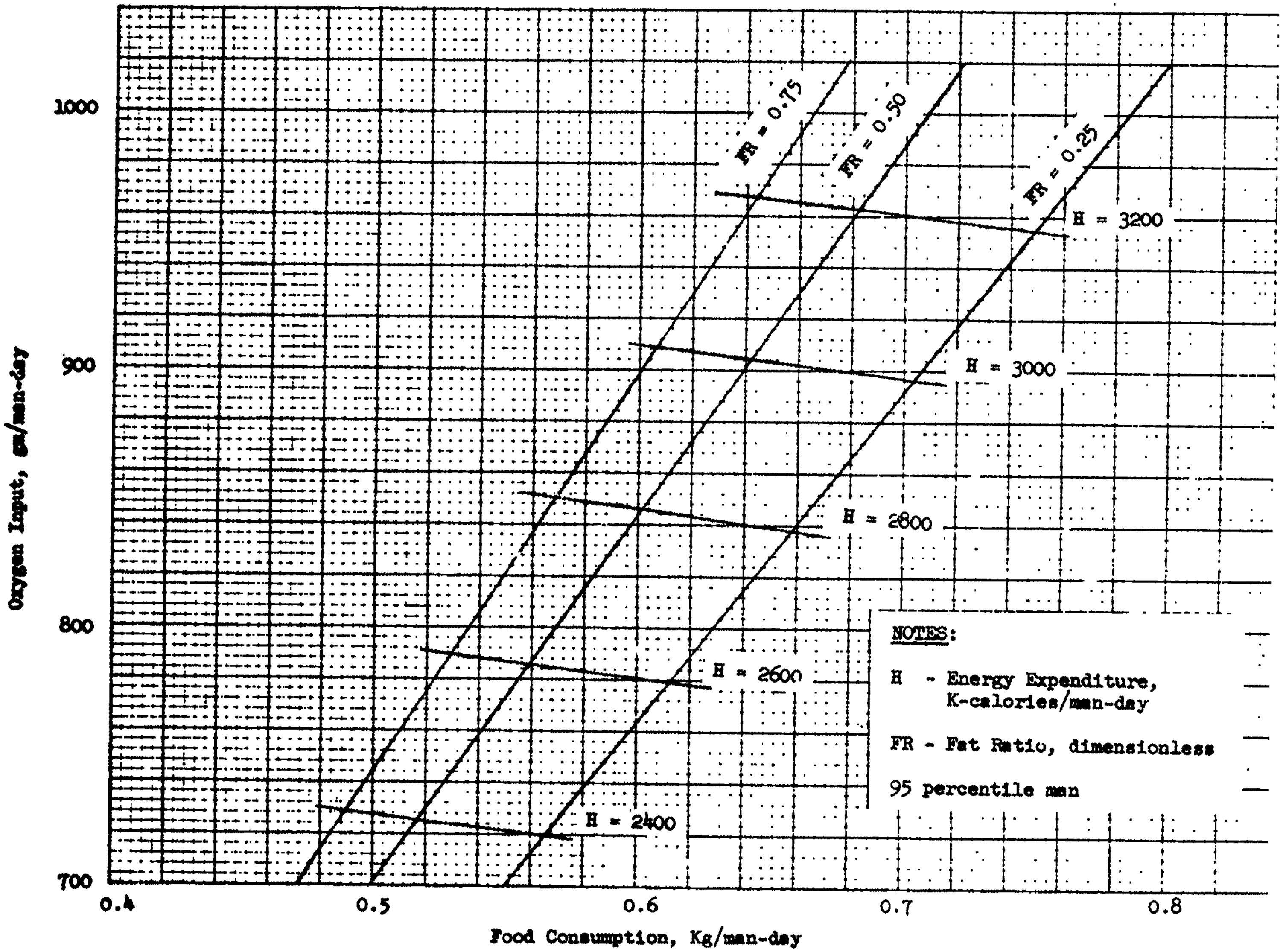


Figure 3-23. Relationships Between Food and Oxygen Consumptions

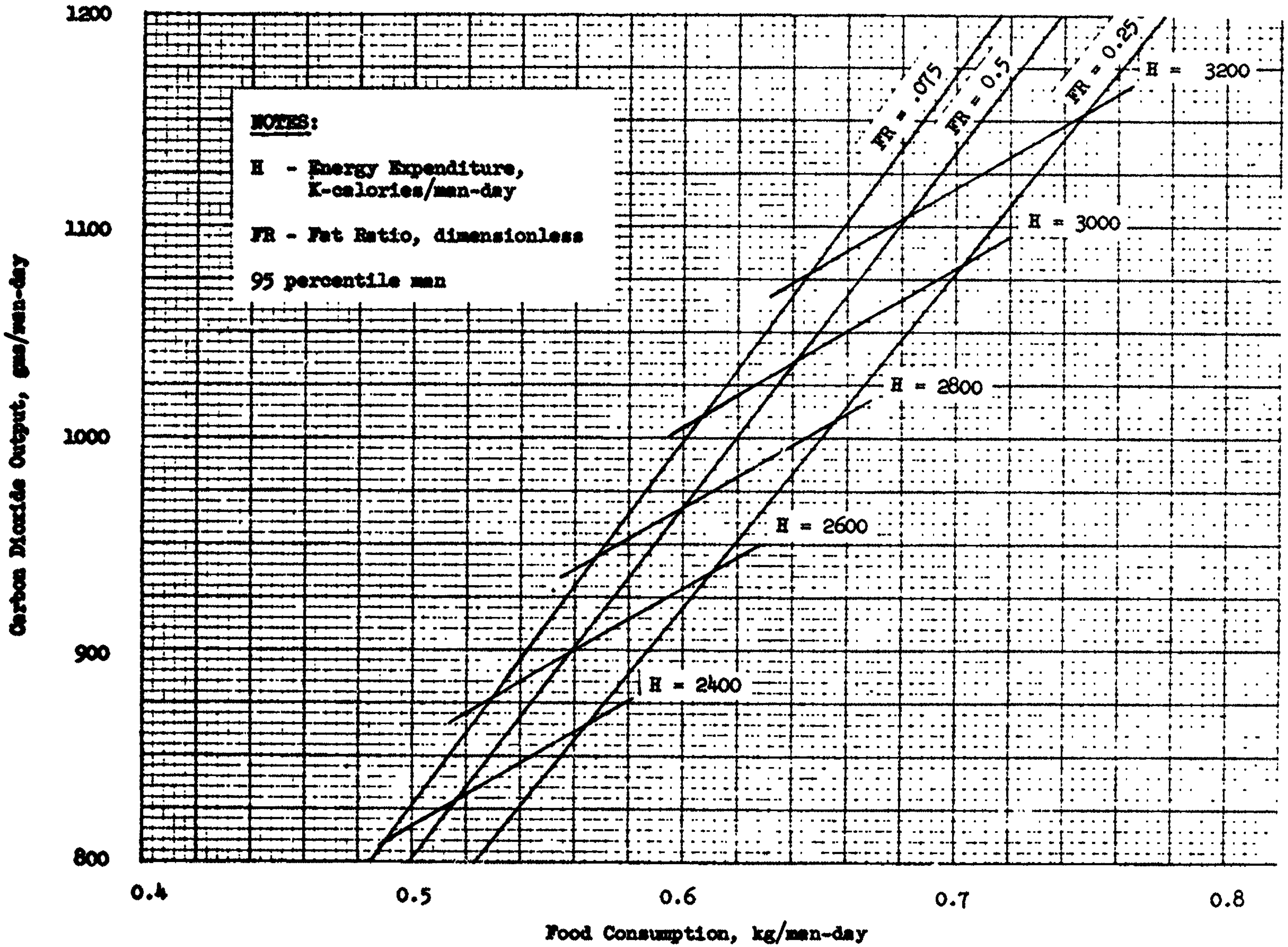


Figure 3-24. Relationships Between Food Intake and CO_2 Output

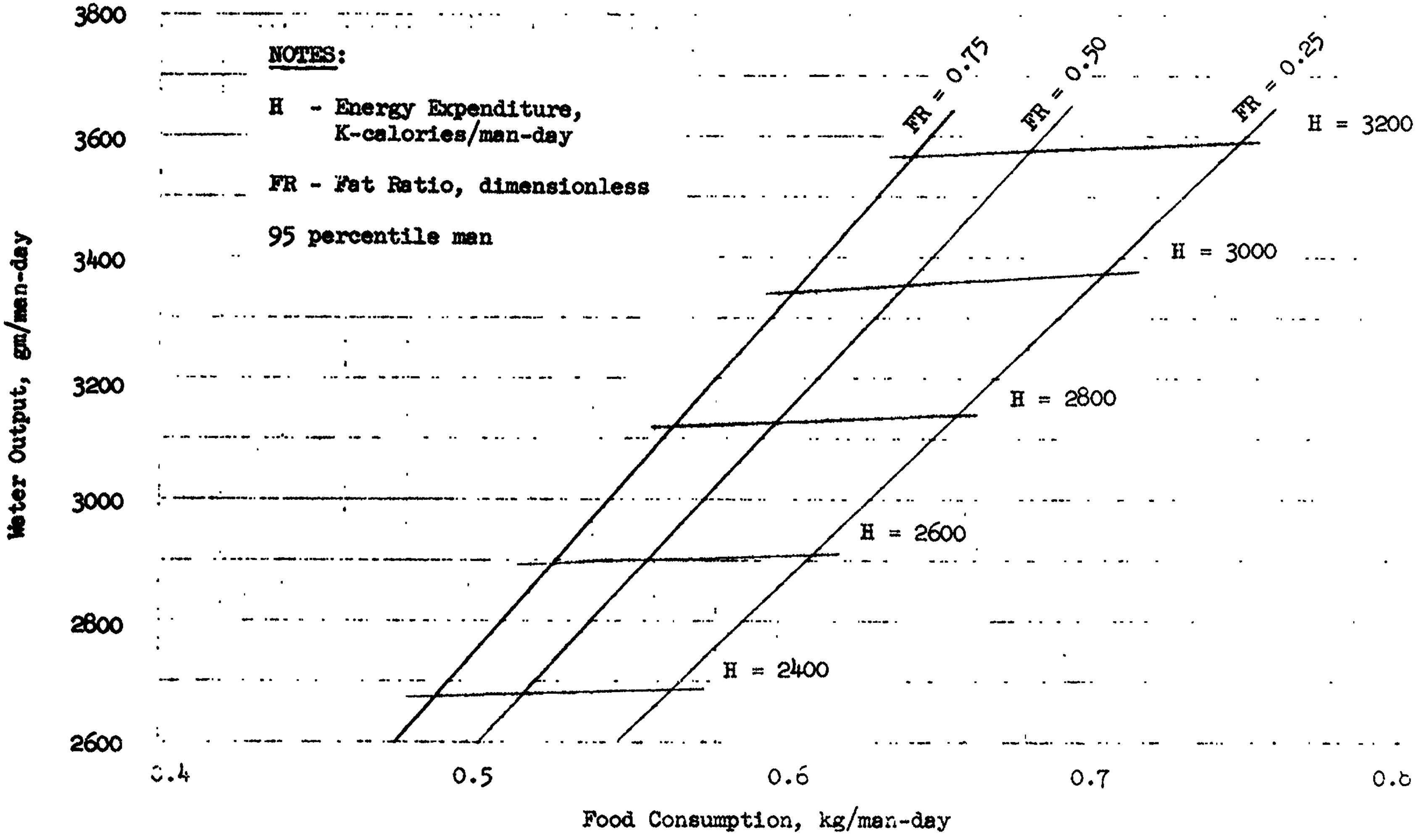


Figure 3-25. Relationships Between Food Intake and Water Output

3.3.4 Comfort Criteria

Crew comfort requirements have significant effects on vehicle design because the design of many components is influenced by cabin atmospheric conditions. Comfort criteria include those combinations of atmosphere pressure, wall and gas temperature, gas circulation, and humidity that create a comfortable environment for the crew. Data presented in this section are intended to provide the criteria for best human functioning for various levels of oxygen, carbon dioxide, humidity, and temperature.

Data from Reference 3-16 illustrate some of the effects of these variables. The test data indicate that only minor temperature differences exist in different atmospheric mixtures for a crewman with no clothing. However, for crewmen with light to medium clothing, an appreciable difference in comfort temperature levels as functions of clothing and atmospheric composition are given in Table 3-6. Data were obtained from test runs at 0.35, 0.49 and 0.703 kg/cm^2 and were extrapolated for completeness to 1.06 kg/cm^2.

The physiological effects of oxygen partial pressure are indicated in Figure 3-26. The minimum level is governed by the need of sufficient oxygen partial pressure to maintain blood oxygen saturation. The maximum oxygen tolerance level is a toxicity limit. According to several investigators, the lower oxygen partial pressure limit is 190 mm Hg, while its upper limit is in the range of 380 to 425 mm Hg. The sea level equivalent line shown in Figure 3-26 is recommended as a design criterion and will be used in this study.

Figure 3-27 indicates the physiological effects of carbon dioxide concentration in the atmosphere. The normal ambient sea level partial pressure of CO_2 is less than 1 mm Hg. However, no noticeable physiological or psychomotor changes have been observed with CO_2 partial pressures of up to 8 to 12 mm Hg under tests which exceeded one month in duration. Even higher levels of CO_2 may be tolerated for short periods such as in emergency situations. Review of current research and literature indicate that CO_2 partial pressure level in space vehicle atmosphere (Figure 3-27) should be of the order of 3 to 8 mm Hg.

For unimpaired human performance, the physiological tolerances to humidity as a function of dry and wet bulb temperatures, and an 80% nitrogen, 20% oxygen atmosphere are presented in Figure 3-28. Since the relative humidity lines shown are essentially straight lines the criteria shown may be used for

Table 3-6

EFFECTS OF ATMOSPHERE COMPOSITION AND CLOTHING ON COMFORT ZONE TEMPERATURES

Clothing Level	Cabin Total Pressure			
	0.352 kg/cm^2	0.492 kg/cm^2	0.703 kg/cm^2	1.06 kg/cm^2*
He - O_2				
0 CLO**	24.4° - 26.7°C	25.6° - 27.2°C	26.1° - 28.3°C	26.7° - 28.3°C
	(76° - 80°F)	(78° - 81°F)	(79° - 83°F)	(80° - 83°F)
0.5 CLO	22.2° - 23.9°C	23.9° - 25.6°C	25° - 26.7°C	25.6° - 27.2°C
	(72° - 75°F)	(75° - 78°F)	(77° - 80°F)	(78° - 81°F)
1.0 CLO	20.0° - 21.7°C	22.2° - 23.9°C	23.3° - 25.6°C	24.4° - 26.9°C
	(68° - 71°F)	(72° - 75°F)	(74° - 78°F)	(76° - 80°F)
N_2 - O_2				
0 CLO	23.9° - 26.1°C	24.4° - 26.7°C	25° - 27.2°C	25.6° - 27.8°C
	(75° - 79°F)	(76° - 80°F)	(77° - 81°F)	(78° - 82°F)
0.5 CLO	20.0° - 21.7°C	20.6° - 22.2°C	21.1° - 22.8°C	21.7° - 23.3°C
	(68° - 71°F)	(69° - 72°F)	(70° - 73°F)	(71° - 74°F)
1.0 CLO	16.1° - 17.8°C	16.1° - 18.3°C	16.7° - 18.9°C	17.2° - 19.4°C
	(61° - 64°F)	(61° - 65°F)	(62° - 66°F)	(63° - 67°F)

*** Extrapolated from test data at lower pressures.**

**** One "CLO" unit being the thermal resistance of clothing for average comfortable conditions or 0. 155 $\frac{°Km^2}{Watt_t}$ (0. 88 $\frac{°F\ ft^2\ hr}{Btu}$)**

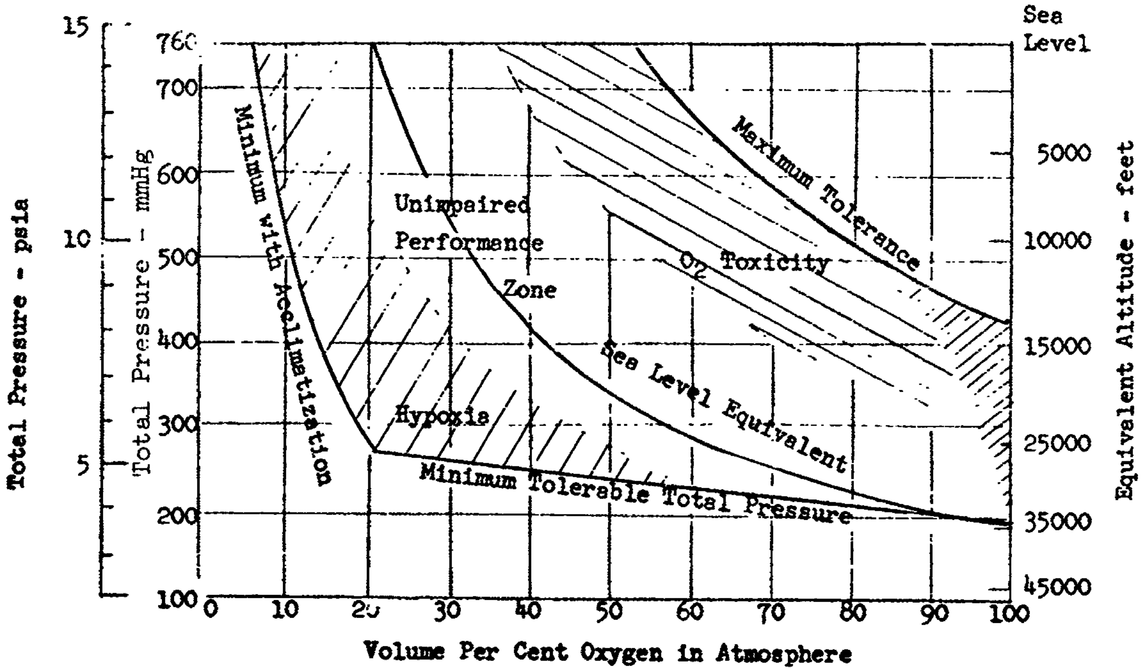


Figure 3-26. Physiological Oxygen Effects

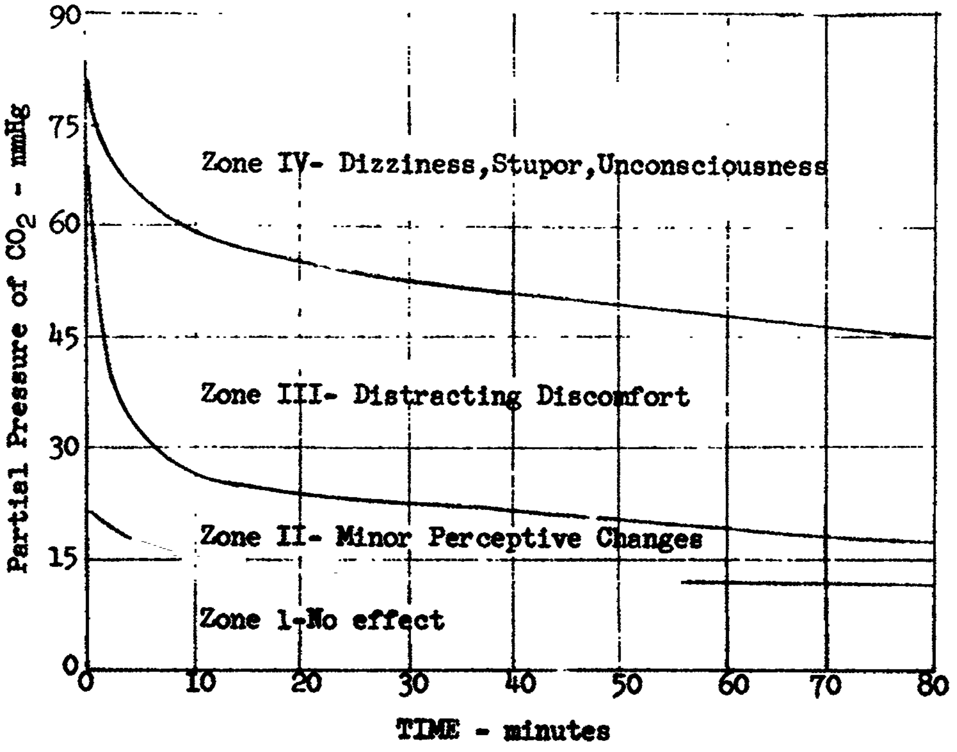


Figure 3-27. Physiological Carbon Dioxide Effects

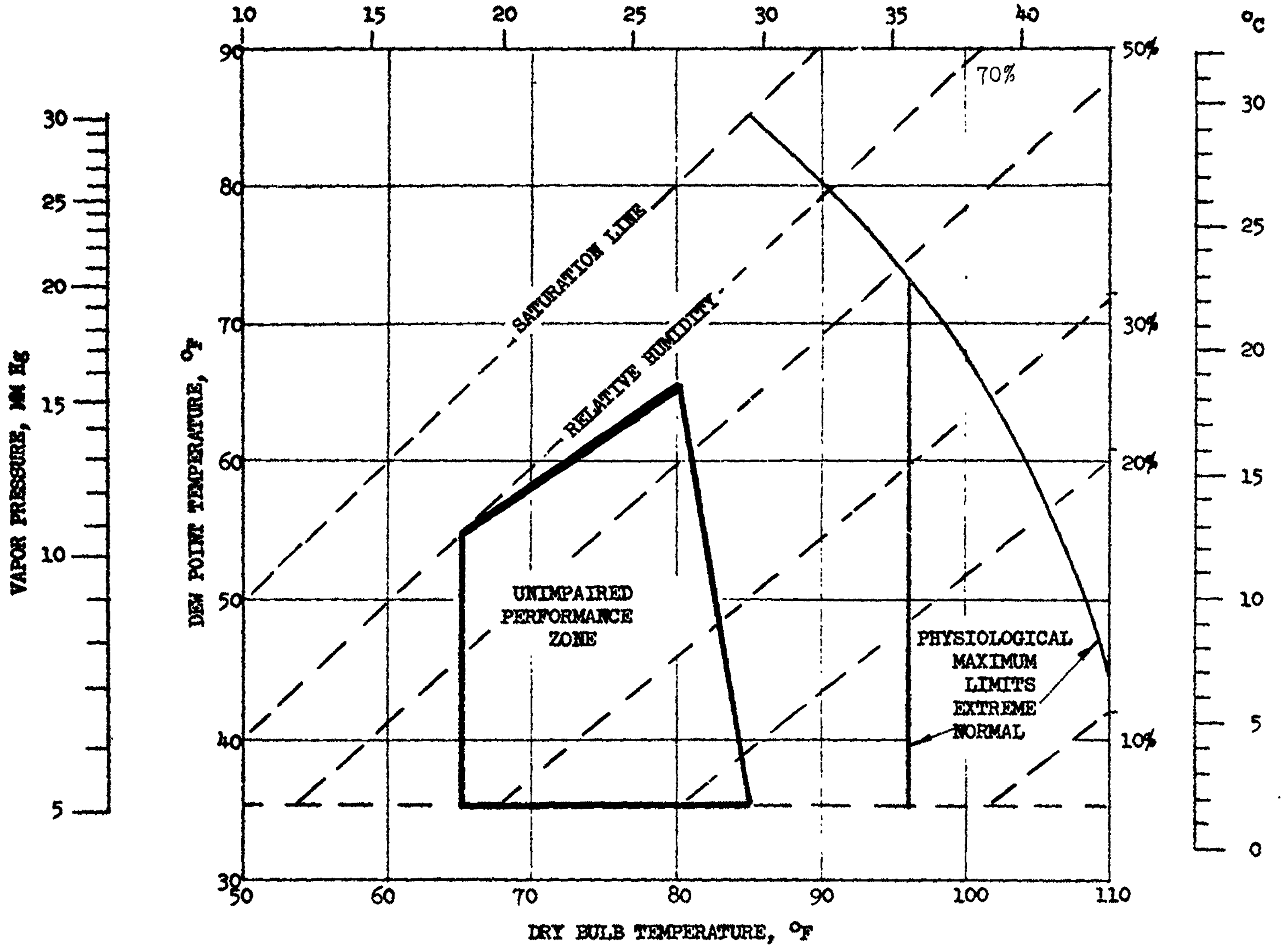


Figure 3-28. Physiological Tolerance to Humidity and Temperature (80% N_2 – 20% O_2 Atmosphere)

any atmosphere pressure likely to be used in spacecraft. For a shirtsleeve atmosphere, with the crew wearing normal light clothing, it is recommended that the conditions be within the unimpaired performance zone. The boundaries of this zone may be altered by two factors: clothing and atmospheric composition.

3.4 VEHICLE REQUIREMENTS

The vehicle requirements are those characteristics of the vehicle which affect the life support system. These are such items as number of cabins, allocation of equipment, functional uses of cabins, vehicle structural concept, and nature or requirements of other vehicle systems. The consideration of these vehicle items in the development of life support systems makes life support systems sensitive to those vehicle requirements which have impact on its characteristics and performance. The implications of vehicle requirements upon the life support system and how these considerations are to be satisfied will be discussed under two major headings, cabin compartmentation and integration of other vehicle systems.

3.4.1 Compartmentation

Compartmentation and the allocation of life support system equipment to vehicle cabins becomes important when the space vehicle is considered to have more than one occupied cabin. A cabin is considered to be a compartment capable of being separately pressurized. It is assumed that hatches connect adjacent cabins and that generally these hatches would be open. In a real space vehicle, heat, water vapor, CO_2, and the basic cabin atmosphere would slow through these hatches causing variations in loading on the life support system in the respective cabins. For this study, however, uniform cabin atmospheric temperature, atmospheric pressure, humidity, CO_2 level, and trace contaminant level are assumed for all cabins so that the necessity of allowing for these flow effects between cabins is obviated. Some types of equipment would logically be provided in each cabin and others would most likely be provided in only one cabin. For example, equipment closely associated with crew comfort, such as cabin heat exchangers, would be expected to be located in each cabin. On the other hand, storage tanks for expendable materials such as oxygen and water would be expected to be stored in one location. For purposes of this study, lack of significant impact of equipment operation upon cabin atmospheric constituent levels and atmospheric temperature permitted the assumption that the equipment could be located in any cabin. Other considerations such as efficient space utilization and operational requirements were used to determine the specific location of other equipment in the vehicle. Equipment which does have a significant impact upon the atmospheric constituent levels and atmospheric temperature were assumed to be located in each cabin. The equipment provided in each cabin potentially achieves significant subsystem reduncancy; but the level achieved depends substantially upon the specified design criteria and overload capability of the equipment. For example, when the equipment in each cabin is sized to accommodate the entire crew, a high level of redundancy is achieved. The specification of the percent of the total crew to be accommodated in each cabin is one of the input variables to the life support system.

Figure 3-29 shows schematically the distribution of life support system equipment for a space vehicle with two occupied cabins. Equipment associated with control of the crew comfort, that is, cabin temperature, humidity, CO_2 level, and trace contaminant level, have been assumed to be located in each cabin, Thus each cabin would contain a cabin heat exchanger and associated fan; and an atmospheric purification loop containing a dehumidifying condenser, a particulate filter, and a CO_2 removal device. If desired, a catalytic burner and activated charcoal could be included in each cabin. More detailed rationale used in locating the equipment is given in the following paragraphs.

3.4.1.1 Oxygen Recovery and Gas Storage

Design for real space vehicles utilizing CO_2 reduction may not include O_2 recovery equipment in all cabins since O_2 recovery is not necessarily critical to maintaining individual cabin O_2 pressure levels, especially when O_2 recovery is used in conjunction with O_2 storage. For this study, the oxygen recovery equipment is assumed to be located in each cabin. Providing O_2 recovery in each cabin does provide additional redundancy to the overall life support system especially when the equipment in each cabin is sized to accommodate the requirements imposed by the complete crew. This equipment sizing capability was provided for in this study. Depending on the mission duration it is found that for most O_2 recovery systems the expendable weights are much larger than the equipment weights so that the weight variations between systems using single or multiple sets of equipment are generally small. Oxygen recovery systems which operate directly on the CO_2 in the cabin atmosphere (molten carbonate)

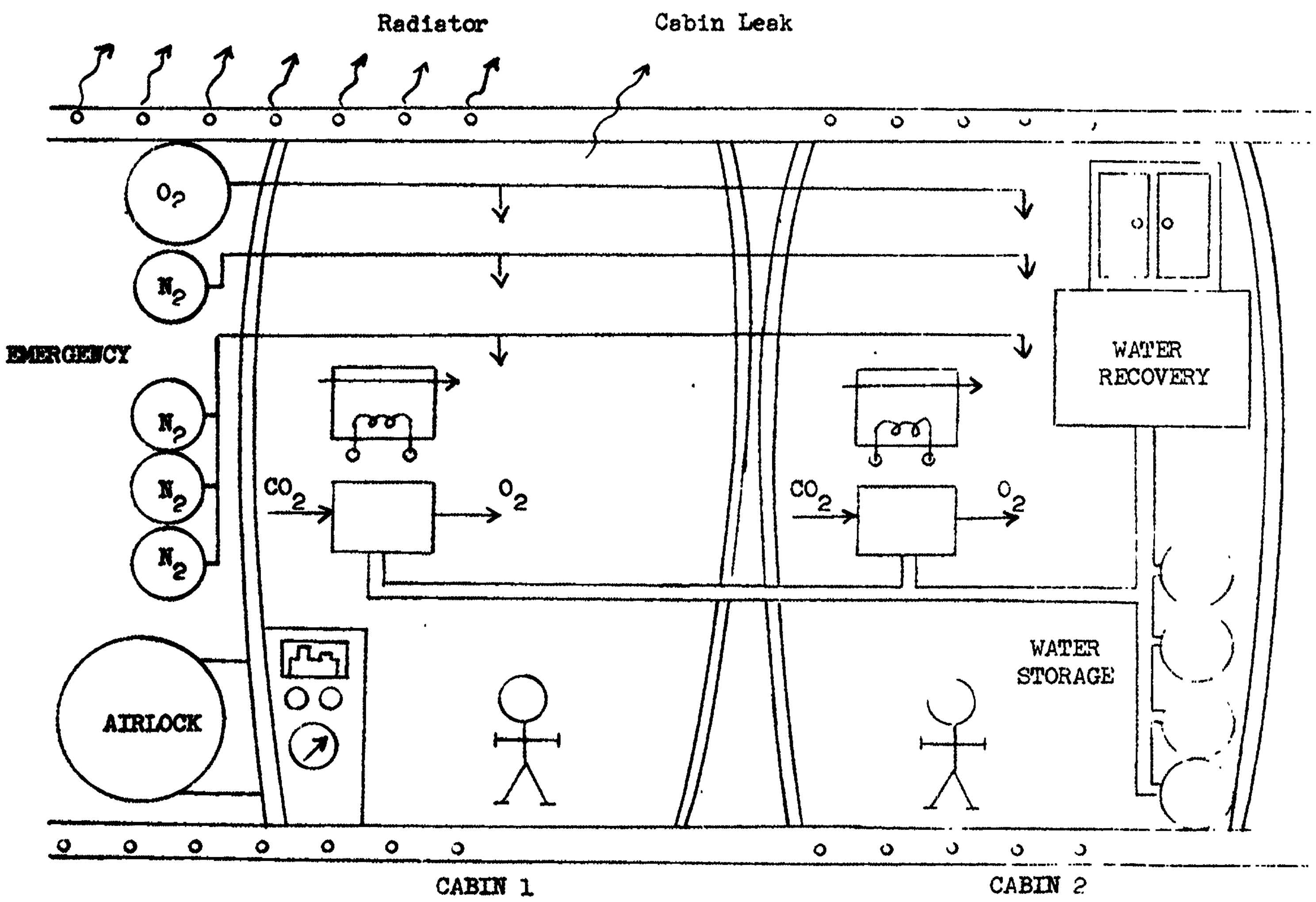


Figure 3-29. Two Occupied Cabins

or on the water vapor in the cabin atmosphere (water vapor electrolysis cell) are inherently very adaptable to this concept of providing separate O_2 recovery equipment in individual cabins.

The gas storage for all cabins is considered to be provided in a group of tanks located in any occupied cabin or in a thermal environment elsewhere in the vehicle but similar to that in the occupied cabin. The required redundancy in gas storage can be achieved by specifying the number of storage tanks. The reliability and the inflight repairability of the distribution system connecting the tanks and the individual cabins are quite high. It was assumed to be unrealistic to provide individual gas storage equipment for each cabin.

3.4.1.2 Crew Living Quarters

Most of the subsystem equipment has been assigned to the highest numbered cabin for each individual space vehicle concept considered. This highest numbered cabin (Figure 3-29) is considered to contain the crew's living quarters and appropriate subsystem equipment. This subsystem equipment includes waste management collection devices for urine and fecal material, water recovery processing equipment and water tanks, most of the crew/crew support and crew accommodations subsystem equipment, and the food supply subsystem processing equipment.

The considerations which follow were involved in developing these assignments of subsystem equipment to the living quarters area. As presently conceived and implemented, there is a negligible effect of the above waste management equipment on cabin atmospheric temperature or on cabin atmospheric composition. Therefore, this equipment does not have to be assigned to a particular cabin; however, it is anticipated that this equipment, as used during normal operating conditions, should be located in the living quarters. It is further anticipated that water recovery processing equipment should generally be located in the cabin containing the collection devices for urine, fecal material, and waste water from washing and food preparation procedures. In accordance with this concept, it was assumed that all water recovery processing equipment be located in the highest numbered cabin. Many of the functional methods for water recovery include processes which reject significant amounts of heat to the surrounding cabin atmosphere, and it is necessary to consider these heat loads in determining the total heat load for the highest numbered cabin. The water storage tanks used in accomplishing the requirements of the Water Supply

Subsystem are optionally considered to be maintained at pasteurization temperatures. Heat transferred through their insulated walls adds to the total cabin heat load. These tanks are considered to be located in the highest numbered cabin.

All of the equipment in the crew accommodations subsystem which reject heat to the cabin atmosphere are considered to be located in the highest numbered cabin. These include equipment for physical fitness, medical monitoring, medical data management, medical care, EVA support, and food preparation. Also, most of the equipment included in the crew/crew support subsystem would be located in the same cabin as the living quarters. Crew safety devices, lights, and low gravity locomotion devices are located in each cabin.

3.4.1.3 Cooling and Heating Loops

It is assumed that there is available in each cabin heated and cooled fluid capability. These two fluid supply requirements are determined from the summation of the individual cabin and equipment needs. The space radiator is connected to the coolant loop through an interface heat exchanger, thus affording system isolation capability.

3.4.2 Life Support System Integration With Other Vehicle Systems

In the previous section the effects of the space vehicle arrangement upon the life support system were discussed. This section will consider the effect of integrating the life support system into the vehicle and the interfaces and interrelations with other vehicle systems. The items to be discussed are vehicle outer wall concept, particulate radiation and meteoroid protection methods, other system cooling, and electrical power demands.

3.4.2.1 Vehicle Structure

As noted in Subsection 3.4.1, for purposes of this study it is assumed that one or more occupied cabins each capable of being separately pressurized are provided in the space vehicle. The number of cabins, vehicle cylindrical diameter, and individual cabin volumes may be specified. The outer cylindrical wall of the cabins may serve several functions. The wall model assumed in the study is shown in Figure 3-30. This wall is considered to be modified as necessary from one based strictly on structural criteria to one which may provide adequate particulate radiation and meteoroid shielding and

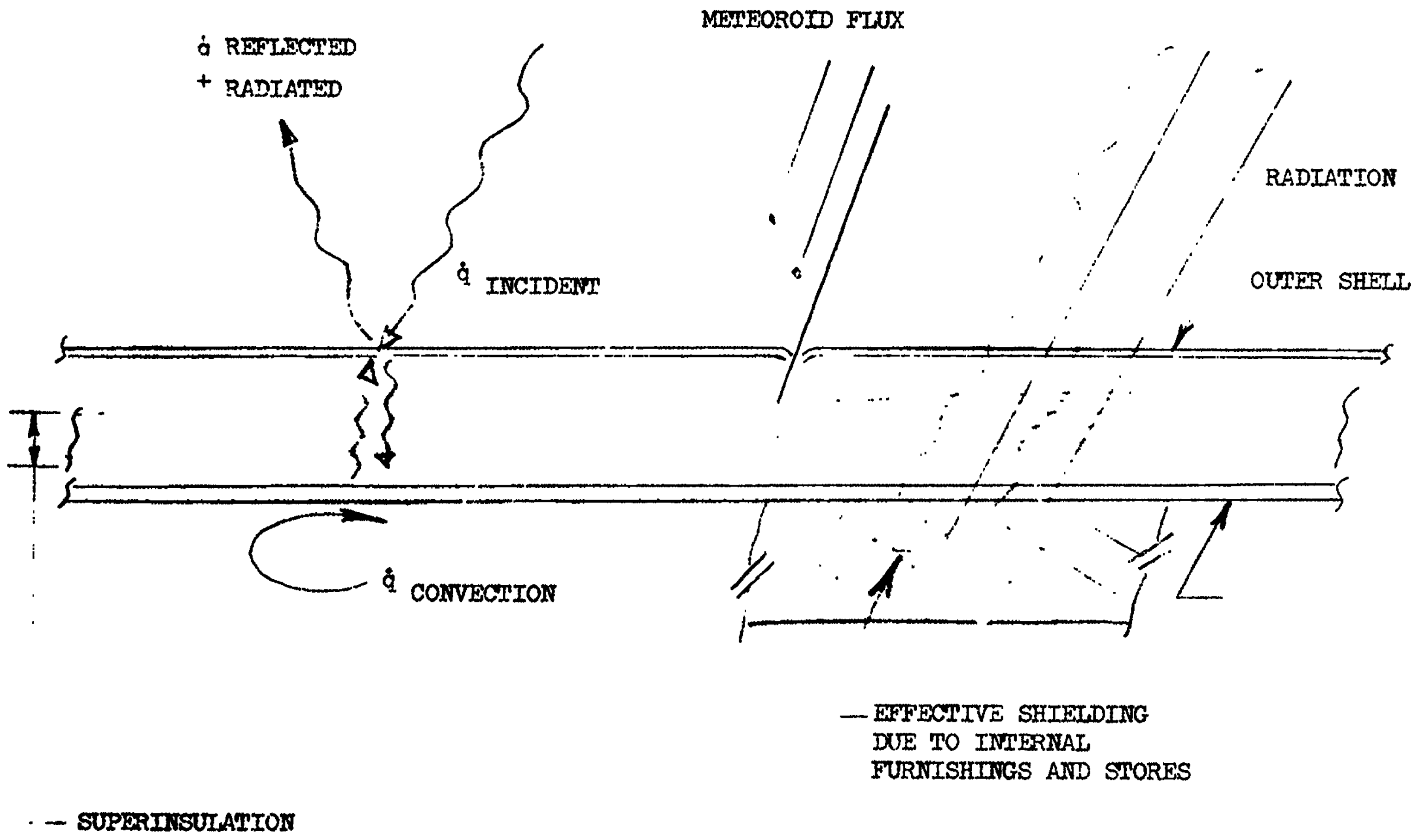


Figure 3-30. Manned Vehicle Cabin Wall Model

providing adequate thermal control characteristics. The outer shell of this wall is considered to provide at least part of the required external surface area for the life support system space radiator. Any required additional radiator area is achieved through lengthening the vehicle outer shell at the specified vehicle diameter.

Superinsulation is sized for cabin thermal control purposes and the insulation is located between the inner and outer shells. Besides satisfying thermal control requirements, the insulation participates in meteoroid and radiation shielding. The inner shell serves as the cabin pressure shell and also contributes to the meteoroid and radiation shielding.

3.4.2.2 Meteoroid and Particulate Radiation

The vehicle outer structure provides the basic protection from meteoroid and particulate radiation. For meteoroid protection the structure is similar to a Whipple bumper. The outer shell is assumed to be thickened to satisfy the design needs. The influence of the superinsulation and the inner shell are included in this determination. And the protection penalty is that metal required to be added to the outer shell over and above that necessary for structural, thermal and pressure requirements imposed on the vehicle wall.

Depending upon the type of space mission, whether Earth orbital or planetary, two concepts for radiation protection are assumed. For the Earth orbital vehicles, all the enclosed vehicle living volume is assumed to be protected. While accounting for radiation shielding provided by the vehicle walls, any additional required radiation shielding, assumed to be located adjacent to the vehicle inner wall, is determined. Determinations of location and packaging requirements for life support equipment and other vehicle equipment in attempts to effectively achieve radiation shielding distributed uniformly over the surface of the inner shell are beyond the scope of this study. However, weights, volumes, and sizes of life support system equipment, expendables, and accumulated materials which are calculated by the computer program can be used in conjunction with layout drawings in assessing the effective shielding obtainable with these items. Major potential accumulated materials which may be considered for such use include the following:

1. Urine and fecal material. Storage of collected materials can be provided. Recovery of water from urine and/or fecal material provides available solids.

2. Carbon. Some CO_2 reduction methods and synthetic food processing methods generate carbon.
3. Water. Complete or nearly complete water recovery methods and synthetic food processing methods can result in available excess water.

Accumulated material weights and volumes are based on those available at the end of missions; thus, it is assumed that accumulated materials needed for protection are available and thus are not removed during resupply operations.

For planetary missions, the vehicle walls provide the primary protection; however, for active solar flare periods, the crew members are assumed to have access to a storm shelter, or biowell. A biowell could be optionally provided if desired for protection from solar flares during earth orbital missions. For each mission, the lightest combination of required shielding for the cabin wall (to provide protection from geomagnetically trapped radiation) and for the biowell (to provide protection from solar flares) would be selected. The radiation shielding determined for cabin walls supplements the biowell shielding in providing protection for solar flares. The radiation computations assume a spherical enclosure and do not explicitly use any particular local surface area of the occupied cabins, and thus, the biowell can be assumed to be located within any of the occupied cabins.

3.4.2.3 Heating or Cooling

Heat generated by equipment other than that included in the life support system and which is to be accommodated by the life support system thermal control subsystem is specified as being rejected to cabin atmospheres and/or transferred to the included liquid coolant loop at cold plates. Required heat for a liquid heating loop is determined when functional methods requiring this heat are needed. It is assumed that this heat could be available as waste heat from the power system, supplied by resistive elements, or generated by a heat source such as a radioisotope heater.

3.4.2.4 Electrical Power

Electrical power requirements for life support systems include continuous power for gas circulation devices such as fans, blowers, and compressors; or intermittent power for such items as EVA support and the gravity conditioner. Some of the equipment, such as the fluid circulation devices, can use either AC or DC power, but on the other hand, electrolysis cells must use DC power.

Power of one type or the other is more readily available depending upon the selected vehicle power system. For example, solar cells generate DC power and dynamic power systems generally generate AC power due to the reduced weight requirements for power conversion and transmission equipment. Data for life support system electrical equipment requiring either AC or DC power are generally not available. One exception to this situation is the case of liquid pumps. The primary source of overall inefficiency in liquid pumps is within the electric motor. Efficiency data for small space type brushless DC and AC motors are available, and, these data have been used to determine overall pump efficiency scaling laws. Determinations of power conditioning equipment for achieving power of particular types and condition for individual equipment are beyond the scope of this study. No distinction is made for the power type required, and the total life support system continuous electrical power need thus includes both AC and DC power.

Intermittent electrical power is required for such items as some waste collection devices, EVA support operations, and gravity conditioning. These power requirements are considered to be very intermittent and of low average daily demand.

3.5 REFERENCES FOR SECTION 3

3-1 M. B. Baker, Geomagnetically Trapped Radiation, Douglas Report SM-47635, dated October 1964.

3-2 J. R. Lilley and W. R. Yucker, CHARGE, A Space Radiation Shielding Code, Douglas Report SM-46335, April 1965.

3-3 D. E. Havens, "Quality Factor Values," McDonnell Douglas Corporation Memorandum A-260-D520-287, dated December 9, 1963.

3-4 Space Radiation Guide, AMRL-TDR-62-86, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base; Dayton, Ohio, August 1962.

3-5 J. W. Snyder, Radiation Hazards to Man from Solar Proton Events, Journal of Spacecraft and Rockets, Vol. 4, No. 6, June 1967.

3-6 R. M. Byke and Brose, H. F., Report on the Optimization of the Manned Orbital Research Laboratory (MORL) System Concept, Douglas Report SM-46085, Volume XIX, Laboratory Mechanical Systems--Environmental Control/Life Support, September 1964.

3-7 O. C. Ledford Jr. and Blakely, R. L., Spacecraft Radiator Analysis, Pages 77-85, Aviation and Space, Published by the American Society of Mechanical Engineers, 1968. Presented at National Aviation and Space Division Conference, Los Angeles, California, June 1968.

3-8 R. G. Watts, Radiant Heat Transfer to Earth Satellites, Paper 64-WA/HT-28 American Society of Mechanical Engineers, Presented at Winter Annual Meeting, New York, New York, December 1964.

3-9 J. A. Stevenson and Grafton, J. C., Radiation Heat Transfer Analysis for Space Vehicles; Air Force Report Number ASD-61-119, Part I, December 1961.

3-10 R. C. Savin, "Sensitivity of Long-Duration Manned Spacecraft Design to Environmental Uncertainties, ASME Meeting, Los Angeles, California, June 16-19, 1968.

3-11 J. M. Deerwester, Reference System Characteristics for Manned Stopover Missions to Mars and Venus, NASA-MAD, Moffett Field, California, July 1967.

3-12 V. C. Frost, Aerospace Meteoroid Environment and Penetration Criterion, Aerospace Corporation Report No. TOR-269(4560-40)-2, August 17, 1964.

3-13 R. C. Savin, "Interplanetary Meteoroid Shielding Requirements", Memorandum, Technical Assistant, Mission Analysis Division to Distribution Mission Analysis Division, August 15, 1966.

3-14 Report on the Optimization of the Manned Orbital Research Laboratory (MORL) System Concept, Volume IV, Douglas Aircraft Company, Contract No. NAS1-3612, Report No. SM-46075, September 1964.

3-15 Bioastronautics Data Book, National Aeronautics and Space Administration Report No. NASA SP-3006, 1964.

3-16 Engineering Criteria for Spacecraft Cabin Atmosphere Selection, Douglas Aircraft Company, Contract No. NASw-1371, November 1966.

Section 4
PARAMETRIC RELATIONS AND SCALING LAWS

This section contains the life support system equipment parametric data which were developed for this study. These data characterize equipment weight, volume, required electrical power, cooling, and heating. Data from this section have been used to specify the parametric relations and scaling laws for prepared baseline life support systems as computer program input data. The functional methods used in formulating these selected baseline systems are outlined in Volume III. The development of the parametric data presented in this section depended on currently available prototype and preprototype equipment data. These data should be expected to change as equipment development and testing efforts continue. To allow new and different equipment parametric data to be expeditiously inserted into the computer program, considerable effort was expended in devising an associated input data procedure which is easy to use. The life support equipment, component, and system information obtained from the current literature and a vendor survey was used to help develop and validate the parametric relations and scaling laws. These data are referenced throughout the sections. Table 4-1 indicates for the major life support systems areas an estimation of development status. The subsystems or components for which parametric data were developed as a part of this study are indicated in the table. Acknowledgement is given to the following government and industrial organizations for their assistance in supplying engineering life support information which proved highly beneficial and valuable for this study.

Aerospace Medical Research Laboratories, WPAFB
Air Force Flight Dynamics Laboratory, WPAFB
ARDE, Inc.
Atlantic Research Corporation
Battelle Memorial Institute
Beckman Instruments, Inc.

Table 4-1

LIFE SUPPORT SUBSYSTEM DEVELOPMENT STATUS (page 1 of 3)

	STATUS*					Parametric and Analytical Data Developed
	1	2	3	4	5	
I. ATMOSPHERE SUPPLY AND CONTROL						
1. Subcritical Storage and Supply	■	■				●
2. Supercritical Storage and Supply	■	■	■	■	■	●
3. Gaseous Storage and Supply	■	■	■	■	■	●
4. Perkin Elmer Mass Spectrometer Multiple Gas Sensor	■	■	■	■		●
5. Beckman Paramagnetic O_2 gas Sensor	■	■	■	■	■	●
II. OXYGEN RECOVERY						
1. Sabatier with Methane Vent	■	■	■	■		●
2. Sabatier with Acetylene Vent	■					●
3. Sabatier with All Hydrogen Recovered	■					●
4. Bosch	■	■	■			●
5. Solid Electrolyte	■					●
6. Molten Carbonate	■					●
III. WATER ELECTROLYSIS						
1. Double Membrane Electrolysis Unit	■	■	■			●
2. Water Vapor Cell	■	■				●
3. KOH Absorbent Matrix Unit	■	■	■			●
4. Porous Electrode Unit	■	■				
5. Rotating Hydrogen Diffusion Cell	■	■				●
IV. CARBON DIOXIDE COLLECTION						
1. LiOH Expendable	■	■	■	■	■	●
2. Regenerative Molecular Sieve with Vacuum Desorption	■	■	■	■		●
3. Regenerative Molecular Sieve with O_2 Recovery	■	■	■	■	■	●
4. Carbonation Cell	■	■				●
5. Magnesium Oxide	■					
6. Solid Amine	■	■				●
7. Electrodialysis	■					●
V. TRACE CONTAMINANT MONITORING AND CONTROL						
1. Toxin Burner	■	■	■	■		●
2. Charcoal Adsorption, Particulate Filters and Chemisorbent Beds	■	■	■	■		●
3. Mass Spectrometer/Gas Chromatograph	■	■				●

Table 4-1 (page 2 of 3)

	STATUS*					Parametric and Analytical Data Developed
	1	2	3	4	5	
VI. THERMAL CONTROL						
1. Space Radiators and Heat Transport Fluid	■	■	■	■	■	●
2. Water Boiler	■	■	■	■	■	●
3. Absorption Cycle	■					
4. Cryogenic Cooling System	■	■				
5. Electrical Heaters and Waste Heat	■	■	■			●
6. Isotope Heaters	■	■				
VII. HUMIDITY CONTROL AND WATER SEPARATION						
1. Condenser with Liquid Gas Separation by Porous Plate	■	■	■			
2. Condenser with Liquid Gas Separation by Wick Heat Exchanger	■	■	■	■		
3. Condenser with Liquid Gas Separation by Mechanical Spin	■	■	■			
4. Condenser with Liquid Gas Separation by Vortex Tube	■					
5. Condenser with Liquid Gas Separation by Hydrophobic/Hydrophilic	■	■	■	■		●
6. Condenser with Liquid Gas Separation by Membrane	■	■				
7. Vapor Electrolysis	■	■				●
VIII. WATER MANAGEMENT						
1. Open and Closed Loop Air Evaporation System	■	■	■	■		●
2. Vapor Pyrolysis System	■	■				●
3. Vacuum Distillation Unit	■	■				
4. Membrane Diffusion/Permeation	■	■				
5. Vapor Compression Unit	■	■				●
6. Electrodialysis	■	■				●
7. Multifiltration	■	■	■	■		●
8. Reverse Osmosis	■					
9. Electrolytic Pre-treatment	■					
IX. WASTE MANACEMENT						
1. Vacuum/Thermal Dehydration System	■	■	■	■		●
2. Chemical Treatment System	■	■	■			
3. Incineration Unit	■	■				
4. Activated Sludge System	■	■				
5. Waste Used for Attitude Control	■					
6. Zimmerman Wet Oxidation Waste Reduction Process	■					
7. Gas Entrainment/Centrifugation for Urine Collection and Removal	■	■	■			●

Table 4-1 (page 3 of 3)

	STATUS*					Parametric and Analytical Data Developed
	1	2	3	4	5	
X. FOOD MANAGEMENT						
1. Freeze-dried Food	■	■	■	■		●
2. Glycerol	■					●
3. Algae	■					
4. Hydrogenomonas	■					●
XI. PERSONAL HYGIENE						
1. Shower with Airflow Directed Droplets	■	■				●
2. Sponge Cleaner	■	■	■			
3. Mechanical Vacuum Shaver	■	■	■			●
XII. BIOLOGICAL CONTROL AND MONITORING						
1. Filters Regenerated by Killing Microbes by Heat	■	■	■	■		
2. Silver Ion Generator	■	■	■			●
3. Ultra Violet Light	■	■	■	■		
4. Viable Sampling by Membrane Filtration	■					
5. Optical and Resistance Measurement	■	■				

*NOTES

1. Basic Research and Development Stage
2. A Working Prototype Subsystem
3. Prototypes Have Been Integrated and Tested in a Manned Simulator
4. Prototypes Have Been Integrated and Tested Successfully in a Manned Simulator
5. Flight Tested in Mercury, Gemini and/or Apollo

Beech Aircraft Corporation
Bendix, Instruments and Life Support Division
David Clark Company, Inc.
Foote Mineral Company
General Dynamics Corporation, Convair Division
General Dynamics Corporation, Electric Boat Division
Goodyear Aerospace Corporation
LTV Aerospace Corporation
MSA Research Corporation
NASA, Ames Research Center
NASA, Manned Space Center
NASA, Office of Advanced Research and Technology
Northern Research and Engineering Corporation
Ocean Systems, Inc.
The Rand Corporation
TRW Equipment Laboratories
Union Carbide Corporation, Linde Division
United Aircraft Corporation, Hamilton Standard Division
United Aircraft Corporation, Pratt and Whitney Aircraft Division

In addition to describing the developed equipment parametric relations and scaling laws, analytical procedures used in determining heat and mass balances and in sizing particular equipment are presented. Examples of equipment sized by analytical procedures provided directly in the computational logic include space radiators and dehumidifying condensers. These analytical procedures for sizing equipment are the exception rather than the rule in the developed computational logic.

Life support system functions are assigned to individual subsystems and interactions between these subsystem functions have been ordered in the developed computational logic. The flow of the computational logic through the various subsystems with individual determinations of equipment characteristics is outlined in Subsection 4.1.1.

Presented in this section, is the development of mass and energy balance equations and life support system characteristics and scaling laws in the following order:

- Atmosphere Control
- Thermal Control Subsystem
- Water Supply Subsystem
- Waste Management Subsystem
- Food Supply Subsystem
- Crew and Crew Support Subsystem
- Crew Accommodations Subsystem
- System Controls Subsystem
- Spares Provisioning

4.1 GUIDELINES

No two spacecraft planners or life support system analysts use the same definition of what equipment, subsystems, and man support items constitute the life support system. This does not mean that each conceived manned spacecraft does not have sufficient supplies and equipment to support the crew. What it does indicate is that each designer has a different concept as to the manner in which the various equipments are related to spacecraft systems. It is the purpose of this section to give the rationale behind the parametric relations and scaling laws developed, the ordering and responsibilities of the subsystems to compose a life support system, and the assessments of the components and subsystem interrelations and interactions.

4.1.1 Subsystem Responsibilities and Interactions

For this study, the life support systems are considered to be comprised of eight subsystems which are defined in terms of their assigned functional responsibilities as follows:

Subsystem	Functional Responsibilities
Atmosphere Control	Control of cabin pressure. Stored O_2 and diluent supply. Airlock pumpdown. Recovery of O_2 from collected CO_2 and/or water.

Subsystem	Functional Responsibilities
Thermal Control	Cabin atmosphere circulation. The control of temperature and humidity. Heating and cooling source. Cabin wall insulation, heat sinks, heat source and hardware circuitry included.
Water Supply	Water storage tanks, sterilization requirements, and the water distribution system. Recovery of water from urine, respired and perspired water, wash water and fecal material.
Waste Management	Collection, disposal, and storage for reclamation or accumulation of CO_2, urine, fecal material, and refuse. Removal of trace contaminants.
Food Supply	Stored food, processing of food from wastes, and food preparation requirements.
Crew/Crew Support	Spacesuits and clothing, EVA support equipment, first aid and medical supplies, fire extinguishers, personal items, and biomedical data equipment.
Crew Accommodations	Living, work, and recreational facilities, gravity conditioners, lights, and biomedical instrumentation.
System Controls	Automatic and manual devices, functional controls, and process monitoring equipment for the complete life support system.

The desired functional responsibilities are accomplished by providing the necessary individual components and component assemblies. These components and component assemblies are grouped as required in accomplishing the required task, and these groups are operated as and are referred to as "functional groups".

In developing the computational model and logic which would be used to characterize the life support system, the same dependent and independent variables which would govern the operation of an actual life support system needed to be determined. From these system variables, it was apparent which specific variables were necessary to describe and characterize each subsystem, component, or piece of equipment analytically. The methodology used for these analytical models was, first, to establish the sizes and mass and energy flows for each of the components; and second, to depict specific components as a function of mass flow, energy requirements, or physical characteristics. Interactions and interrelations between components and subsystems were determined from the processing rates for gas and liquid streams; cooling, heating, and power requirements associated with each item; and maintainence of balances in the mass and energy flows. Figure 4-1 diagrams the interrelations between the subsystems and the order in which these subsystems are characterized.

A detailed listing of the data which must be supplied by the user to perform computations is given in Table 4-2. This table lists the subsystems in the order of computations, indicates the input data and the components which are characterized in terms of physical dimensions. Input data are considered to be those quantities which are required for the mass flow and energy balance

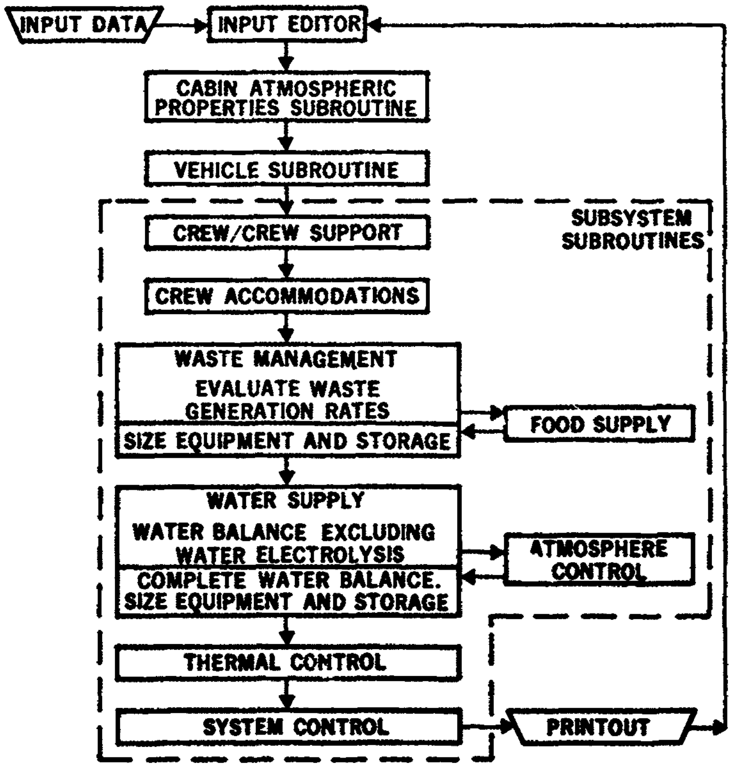


Figure 4-1. Life Support System Computational Logic

Table 4-2

INPUT AND OUTPUT DATA FOR LIFE SUPPORT SYSTEM COMPUTATION (Page 1 of 5)

Subsystem	Input Data: User Input	Input Data: Determined by Computational Logic	Functional Item	Output Data: Equipment Weight	Output Data: Equipment Volume	Output Data: Equipment Power	Output Data: Expendables Weight	Output Data: Expendables Volume
w/Crew Support	Crew size	Cabin wall temperature	Mission maintenance and operations time					
	Flight date	Physical properties of cabin atmosphere						
	Mission duration		Crew support equipment					
	Atmospheric pressure, gas composition, temperature and humidity		Space suits and clothing	X	X	X		
			Portable life support system	X	X	X	X	X
	Resupply period		Personal items	X	X	X		
	Expendable design		Data management and storage	X	X	X		
	Crew activity level		First aid, medical and safety	X	X	X		
	Crew fraction per cabin		EVA support	X	X	X		
	Equipment design		Equipment design, crew performance					
	Crew activity level		Sensible heat					
	Crew fraction per cabin		Water respired and perspired					
	Crew percentile		O_2 consumption					
	Fat ratio		CO_2 generation					
	EVA man-hours		Expendable design crew performance					
	Miscellaneous data for detailed biothermal analysis		Food consumption					
			O_2 consumption					
			CO_2 generation					
			Water consumption					
			Water respired and perspired					
			Urine generation					
			Fecal material generation					
ew Accommodations	Crew size							
	Mission duration		Instrumentation and controls	X	X	X		
	Tour of duty		Living, work, and recreation facilities	X	X	X		
			Gravity conditioning	X	X	X		

Table 4-2 (Page 2 of 5)

Subsystem	Input Data User Input	Determined by Computational Logic	Functional Item	Output Data Equipment Weight	Equipment Volume	Power	Expendables Weight	Expendables Volume
Waste Management	Crew size	Physical properties of cabin atmosphere	Water generated by CO_2 removal (LiOH)					
	Flight date							
	Mission duration	Net of CO_2 generated and lost due to leakage	Water required for CO_2 removal (electrodialysis)					
	Resupply period	Urine generation	H_2 and O_2 generated by CO_2 removal (electrodialysis)					
	Emergency period	Fecal generation						
	Reliability	Refuse generation	CO_2 available for CO_2 reduction					
	Leakage rate	Transfer to Food Subsystem and return	Atmosphere and water lost by CO_2 removal					
	CO_2 pressure							
	Selected normal operation functional methods for CO_2, urine and fecal collection, dumping, and storage	CO_2 required for food processing	CO_2 removal					
			Normal operations	X	X	X	X	X
		Urine required for food processing	Emergencies	X	X	X	X	X
			Refuse collection	X	X	X		
	Selected emergency period functional method for CO_2 removal	Fecal required for food processing	Trace contaminants removal.	X	X	X	X	X
			Urine collection, dumping, and storage					
	Specify trace contaminants removal		Normal operations	X	X	X	X	X
			Emergencies				X	X
	Miscellaneous data for selected functional methods		Accumulated urine					
	Specify tanks for urine storage		Fecal collection and storage					
			Normal operations	X	X	X	X	X
	Cooling fluid temperatures		Emergencies				X	X
	Heating fluid temperatures		Accumulated fecal material					
			Normal cooling requirements					
			Emergency cooling requirements					
			Normal heating requirements					
			Emergency heating requirements					
			Spare parts	X	X			
Food Supply	Flight date	Available CO_2, urine, and fecal for food processing	CO_2, urine, and fecal rates for food processing					
	Specify food recovery		Water required for food processing					
	Functional method for food recovery		Net of wash water plus water generated by food processing					
	Fat ratio for stored food		Stored food	X	X	X	X	X
	Maximum ratio of recovered food to total food		Cooling and heating requirements for stored food					
			Processed food	X	X	X		

Table 4-2 (Page 3 of 5)

Subsystem	Input Data: User Input	Input Data: Determined by Computational Logic	Functional Item	Output Data: Equipment Weight	Output Data: Equipment Volume	Output Data: Equipment Power	Output Data: Expendables Weight	Output Data: Expendables Volume
Food Supply (continued)			Cooling and heating requirements for processed food					
			Accumulated carbon					
Water Supply	**Flight date**	**Total occupied cabin(s) length**	Available water excluding water electrolysis					
	Mission duration	**Respired and perspired water**	Transfer to Atmospheric Control Subsystem and return					
	Resupply period	**Water lost due to cabin leakage.**	Required makeup or accumulated water					
	Emergency period	**Water lost or generated by CO_2 removal.**	Accumulated urine, fecal and condensate residues after processing. Accumulated processing materials.					
	Vehicle diameter							
	Specify water recovery							
	Reliability	**Urine and fecal rates for water recovery**						
	Water storage details:							
	Tank geometry and/or number of tanks, and tank pressure	**Net of wash water plus water generated by food processing**	Water recovery equipment	X	X	X	X	X
		Water consumption	Storage tanks	X	X			
	Sterilization method	**Fecal flush water**	Sterilization	X	X	X		
	Functional methods for water recovery	**Water required for food processing**	Pumps, lines, and miscellaneous equipment	X	X	X		
	Miscellaneous data for selected functional methods:	**Water (liquid and vapor) required for electrolysis:**	Cooling and heating requirements for normal operation					
			Spare parts	X	X			
	Cooling and heating fluid temperatures							
	Process efficiencies							
	Wash water rate							
Atmosphere Control	**Atmospheric pressure and gas composition**	**Physical properties of cabin atmosphere**	CO_2 reduction	X	X	X	X	X
			Water electrolysis	X	X	X	X	X
	Resupply period	**CO_2 available for CO_2 reduction**	Airlock pumpdown	X	X	X		
	Emergency period	**Available water for water electrolysis**	Water for electrolysis			X	X	X
	Number of cabins, vehicle diameter, and cabin volumes		Gas storage			X	X	X
	Equipment design	**Required makeup O_2**	Storage vessel size					
	Crew fraction per cabin	**Net water vapor generation rate exluding water vapor cell requirements**	Spare parts	X	X			
	Expendable design		Water lost due to cabin leakage					
	Crew fraction per cabin	**Available H_2 from electrodialysis CO_2 removal method**	Cooling and heating requirements for normal operation					
	Reliability							
	Number of repressurizations		Accumulated carbon					

Table 4-2 (Page 4 of 5)

	Input Data			Output Data				
				Equipment			Expendables	
Subsystem	User Input	Determined by Computational Logic	Functional Item	Weight	Volume	Power	Weight	Volume
Atmosphere Control (continued)	Atmospheric constituent storage details:							
	Storage method (high pressure, supercritical, or subcritical)							
	Tank geometry and/or number of tanks							
	Selected basic method for O_2 recovery and/or supply							
	Functional methods for CO_2 reduction and water electrolysis							
	Miscellaneous data for selected functional methods:							
	Cooling fluid temperature							
	Process efficiencies							
	Leakage rate							
	Number of airlock uses and associated miscellaneous detail data							
Thermal Control	Crew size	Physical properties of cabin atmosphere	Atmosphere purification loop:					
	Atmospheric pressure, gas composition, temperature and humidity		Ducting	X	X			
		Individual cabin lengths	Condenser	X	X			
	Emergency period	Vehicle outer shell thickness	Water separator	X	X			
	Expendable design	Meteoroid flux data	Blower (normal)	X	X	X		
	Crew fraction per cabin	Pressure drops for condensers, heat exchangers, cold plates, tubing, ducting, space suits, etc.	Compressor (emergency) (CO_2 and trace contaminants removal determined in Waste Management Subsystem)	X	X	X		
	Cabin diameter							
	Reliability							
	Three cooling and heating loop temperature levels.	Cooling and heating fluid flows and heat loads from individual functional methods for normal operation.	Ventilation fan	X	X	X		
			Cabin heat exchanger/fan	X	X	X		
	Cooling and heating inlet temperature levels for particular functional methods.		Cooling loop	X	X			
			Heating loop	X	X			
	Cold plate heat loads	Cooling and heating fluid flows and heat loads from individual functional methods for emergency operation.	Water evaporator (normal)	X	X		X	X
			Water evaporator (emergency)	X	X			
			Interface heat exchanger	X	X			

Table 4-2 (Page 5 of 5)

Subsystem	Input Data User Input	Input Data Determined by Computational Logic	Functional Item	Output Data Equipment Weight	Output Data Equipment Volume	Output Data Equipment Power	Output Data Expendables Weight	Output Data Expendables Volume
Thermal Control (continued)	**Atmosphere cooled equipment heat loads**		Cold plates	X	X			
	Cabin outer shell emissivity		Water pump	X	X	X		
	Water evaporator operational time (if specified)		Radiator loop	X				
			Meteoroid bumpers	X				
	Fraction of cabin walls used as space radiator		Additional structure	X				
			Radiator pump	X	X	X		
	Space radiator details:							
	Specify meteoroid protection							
	Equivalent weight of power							
	Radiator emissivity							
	Specific weight of additional radiator structure							
	Radiator reliability							
	Cabin wall and radiator sink temperatures, or following details for sink temperature computations:							
	Specify orbital or inter-planetary environment.							
	Distance from sun							
	Orientation to sun							
	Absorptivity/emissivity ratios for cabin wall and space radiator							
	Planet radius							
	Planet albedo							
	Orbital altitude							
System Control	**Vehicle diameter** **Baseline system**	Total length of manned cabins	Sensors, wiring, and central control console	X	X			

computations and, subsequently, for the determinations of equipment requirements and characteristics, expendables, accumulated material, the emergency equipment and materials. Some of these input data are specified by the user and some are determined by some computational logic before the subsystem determinations.

Determined equipment and expendable characteristics are emphasized in the output data because they constitute the primary results from the computations. Emergency equipment and materials and accumulated materials which could be used for other purposes, such as radiation shielding, are also indicated in the table. The output data are considered to be of two basic types: quantitative and qualitative. A listing of the items which are considered as quantitative output data are shown in Table 4-3. The qualitative data are not easily obtained or defined, but they may consist of (1) verbal expressions denoting relative advantages and disadvantages of various functional methods, and (2) estimates for flight date or assessment of the state of the art. These verbal expressions may indicate required development areas, relative confidence level, and unique features of various functional methods. The projections of the state of the art for functional method characteristics have been found to be more meaningful when determined for changes in equipment weight. Weight characteristics are intrinsically linked to the many mechanical problems associated with various functional methods. As the mechanical problems are solved, it is reasonable to expect that some weight reductions may be achieved. Examples of these mechanical problems include diffusion of materials through membranes, carbon collection and handling, liquid-gas separation, and catalytic bed operation. Projected volume or power characteristics are more difficult to rationalize than weight characteristics for even clearly designed functional methods. Projections of the state of the art have been applied to key components for various functional methods which indicate promise of some significant weight reduction or development over the next 30 years. Table 4-4 gives several examples of the types of qualitative information developed in conjunction with the quantitative data. Such qualitative items include estimates for the date when flight qualified hardware may be available, indications of the pacing components or technology, and decreases in physical size probable.

Table 4-3

QUANTITATIVE OUTPUT DATA

Vehicle Data	
Meteoroid shield	Weight
Cabin wall radiation shielding	Weight
Biowell	Weight Volume Size
Additional structure for radiator	Weight Size
Life Support System Data	
Subsystem equipment (Projected state of the art applied to key component weights)	Weight Volume Electrical power Geometrical size Required heating Required cooling (sizes life support system space radiator)
Subsystem expendables	Weight Volume
Accumulated material	Weight Volume
Subsystem spares	Weight Volume
Emergency equipment	Weight Volume Electrical power
Emergency power	Electrical power
Emergency cooling	Weight (water for evaporator) Volume
Emergency heating	Required heat

Table 4-4

TYPICAL QUALITATIVE OUTPUT DATA

Subsystem	Functional Method	Qualification
Waste Management	CO_2 removal by electrodialysis	Electrodialysis cell critical component. 1975 flight date
		High current, low voltage
		Membrane porosity, 10% decrease in weight and power possible
Atmosphere Control	CO_2 reduction by Bosch technique	High-temperature (1,600°F) materials
		1970 flight date, carbon removal and storage, 50% expendable weight reduction

4.1.2 Parameterization Methodology

Many of the functional methods for the subsystems have been parameterized by a semi-analytical procedure. Reasons for selecting this procedure in preference to a purely analytical method include: (1) lack of existing or adequate mathematical models, (2) existing prototype configurations have been designed primarily to achieve workable laboratory or development systems with secondary emphasis on satisfying space vehicle requirements such as achieving low weight and volume, and (3) adequate and reliable earth-based configurations do exist for some advanced life support systems but the modifications required to satisfy space vehicle requirements have not been clearly delineated. In most cases, these configurations are comprised of several individual components that are not of flight weight and size.

The procedure used to obtain the functional configurations is outlined as follows:

1. Representative characteristics for individual components are obtained. Included are items such as weight, power requirements, volumes, and cooling and heating loads.

The characteristics are obtained from current published data (References 4-1 through 4-4), interviews and correspondence with equipment developers, or from results of tests of laboratory models by government agencies. It was endeavored to obtain the characteristics in consistent terms. In later system integration of these components the variables used become the independent or dependent variables which define a parametric functional unit. The collected component characteristics data then define the equipment which implements the functional method for a particular case in terms of crew size, mission duration, or some other pertinent variable.

Detailed engineering designs or judgment are used to modify or supplement data when they are clearly not representative of flight qualified hardware.

2. Any available information or data for flight qualified components, subsystems, or systems are obtained. The data are used to qualify the validity of the analytical scaling methods. It was endeavored to have the analytical results agree within ±5 % of the test results.
3. The developed component characteristics as functions of independent variables are summed to obtain the scaling laws for a complete assembly such as that shown in Figure 4-2.

Analytical methods have been used to formulate mass flows and energy balances for life support systems as an aid in determinig normal operational conditions and expendable requirements for equipment. Analytical methods have also been used to determine some equipment sizing procedures; some previously developed methods have been either directly incorporated in the computational logic, or scaling laws have been derived from the analyses and used by the computational logic. Some equipment sizing computer programs are available and these have been used to obtain parametric data for some equipment.

The following subsections describe in detail the application of various methods to various elements of each of the subsystems and the scaling laws and parametric relations which result.

4.2 ATMOSPHERE CONTROL SUBSYSTEM

The Atmosphere Control Subsystem (ACS) is comprised of functional groups which supply stored O_2 and diluent gas to vehicle compartments, provide airlock pumpdown, and recover O_2 from wastes. The requirements of the ACS for a manned spacecraft are to supply oxygen for human physiological needs and to make up the atmospheric constituents lost through spacecraft leakage, airlock operation, and cabin depressurizations. Other life support subsystem equipment may use O_2. The ACS must maintain the oxygen

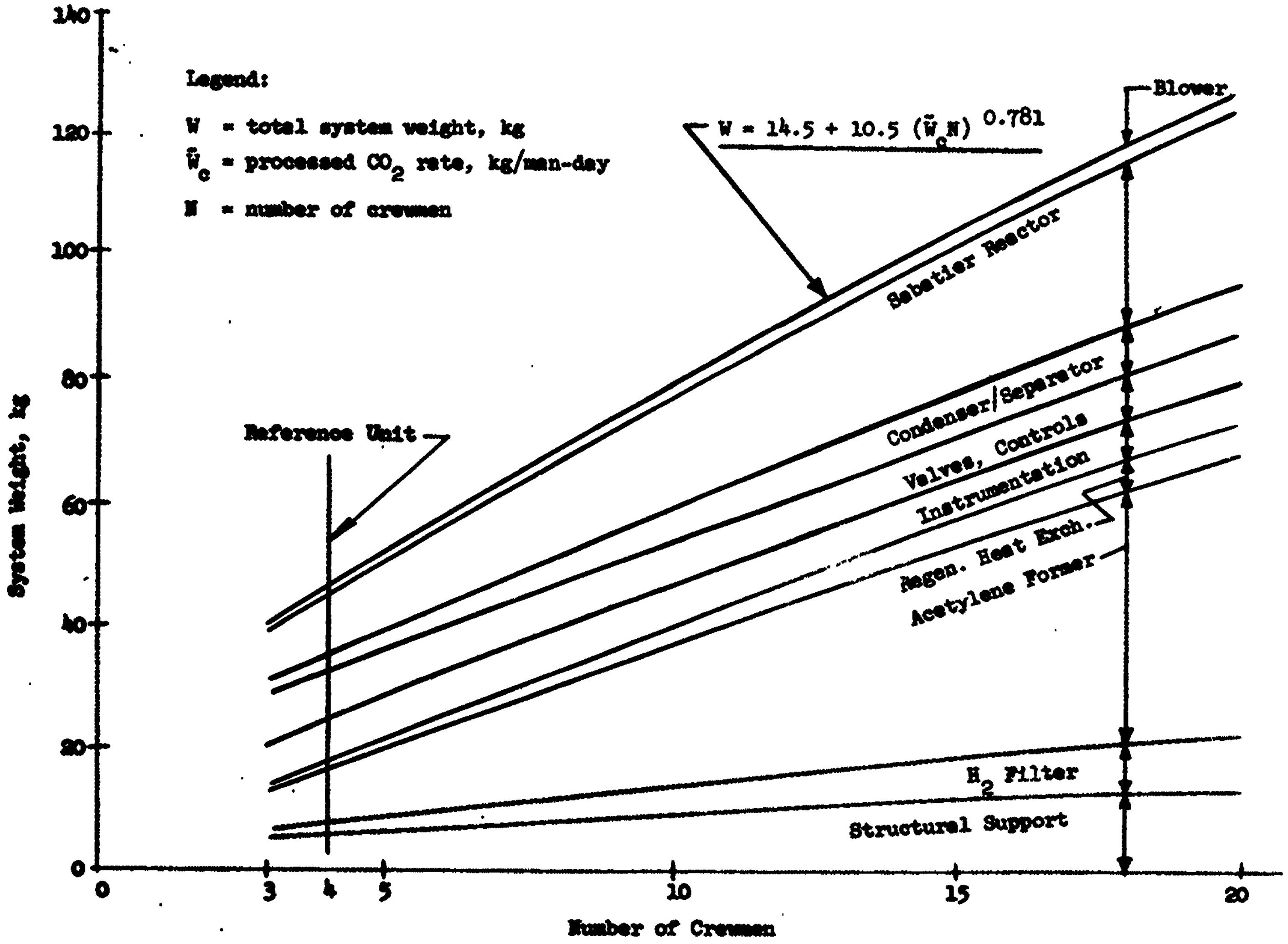


Figure 4-2. Example of Scaling Law Development – Sabatier with C_2H_2 Vent

partial pressure within limits specified by physiological considerations (i. e., 160 mm Hg and above) and control the inert gas partial pressure for a two-gas system to a specified total pressure (i. e., 250 to 760 mm Hg). The ACS must be able expeditiously to repressurize spacecraft cabins, after a complete loss of atmosphere. Stored oxygen and diluent gas must be available for use during emergency periods. As outlined in Subsection 3.1.3, the functional method of high-pressure storage has been selected for providing the atmospheric constituents for both emergency periods and for repressurizations.

The ACS data were obtained and scaling laws were developed for the technological areas as follows:

- Cabin Atmosphere Composition
- Gaseous and Cryogenic Storage Subsystems
- Oxygen Recovery
- Airlock
- Multiple Cabin Consideration
- Cabin Pressure Control and Gas Distribution

4.2.1 Cabin Atmosphere Composition

The cabin atmosphere is composed of at least 160 mm Hg partial pressure of oxygen. The diluent gases considered in this study are nitrogen and helium. Other potential inert gases for use in space vehicle cabin atmospheres include neon, argon, krypton, and xenon. The latter three gases of this group are usually not considered because of scarcity, high molecular weight, and unknown physiological properties, especially in regard to decompression sickness (Reference 4-5). Studies comparing N_2-O_2 and He-O_2 atmospheres indicate a range from 6 to 20% savings in weight can be achieved if helium diluent is used instead of nitrogen (Reference 4-6). The weight saving results principally from a lighter stored gas and the thermal control power saving caused by the allowable cabin comfort temperature level in helium being 1.5° to 4.0°C higher than for nitrogen diluent. Helium loses its advantages if leakage rate is high. The effects on humans from the use of helium for long durations are not well known. However, the weight effects for either helium or nitrogen can be evaluated by hand calculations or with the Fortran parametric program developed under this study.

Neon has thermophysical properties which are intermediate to those of N_2 and He, thus, its stored weights would be intermediate to these gases. Comfortable cabin atmospheric temperatures for Ne-O_2 atmospheres fall between those for N_2-O_2 and He-O_2 atmospheres so that potential reductions in thermal control system weights associated with higher cabin temperatures are intermediate for Ne-O_2 atmospheres. It was considered to be premature to include computational logic for the intermediate Ne-O_2 atmosphere at this time. If future studies indicate significant advantages in weight, volume, or power for systems using Ne-O_2 rather than N_2-O_2, the computational data and logic for Ne-O_2 atmospheres could be added to the Atmosphere Control Subsystem computational scheme.

4.2.2 Gaseous and Cryogenic Storage Subsystem

The gaseous storage methods for the atmosphere gases considered in this study include:

1. High-pressure storage at ambient temperature
2. Supercritical storage at cryogenic temperature
3. Subcritical storage at cryogenic temperatures

High-pressure gas storage weight and volume characteristics were parameterized from data available in the literature. Cryogenic gas storage weight, volume, and power characteristics were parameterized through the use of a digital computer program used to design supercritical and subcritical cryogenic fluid tankage. Both spherical and cylindrical tank shapes were included for high-pressure and cryogenic gas storage. High-pressure gaseous storage is usually heavier than cryogenic storage because of the heavy vessels dictated by the high storage pressure (about 422 kg/cm^2). The primary advantages of high-pressure storage are that the equipment is relatively simple and the gas is readily available for the requirements of rapid repressurization and emergency operation. High-pressure storage weight may be less than cryogenic storage weight for some missions depending upon the standby times or use rates.

The storage of atmospheric constituents at cryogenic temperatures generally entails lower tankage weight. This reduction in weight is attributed mainly to two effects: (1) smaller volumes because the gas is stored as a fluid, and

(2) lower working pressures permit thinner pressure vessel walls. On the other hand, cryogenic systems have the relative disadvantages of more complex control systems, more sophisticated hardware, loss by boiloff, greater electrical power requirements, lower reliability and higher maintenance requirements. There are two thermodynamic conditions, supercritical and subcritical, at which gases may be stored as cryogenic fluids. The tankage weights for supercritical storage are somewhat higher than those for subcritical storage because the greater design pressure level and lower design heat leak for supercritical storage requires heavier wall vessels and more insulation.

Supercritical fluids are in a homogeneous (i.e., single phase) thermodynamic state while subcritical fluids exist as two phases (liquid and vapor) in saturated equilibrium. Subcritical storage has not been demonstrated to be operational for zero-g applications because techniques to draw off vapor selectively have not yet been fully developed. Helium is not feasible to store subcritically because of its extremely low critical temperature of 4°K.

For this study, use of cryogenic storage during emergency periods is not considered generally feasible. The design requirements of a large ready gas volume to satisfy emergency/repressurization supply rates using cryogenic storage are difficult to reconcile as little development effort has been directed toward this goal. Secondly, for missons of extended durations, a standby cryogenic system is impractical because the amount of insulation required to achieve very low boiloff rates during standby would be prohibitive. Numerical substantiation of this point is not available since cryogenic storage vessels have been designed only for essentially constant use rates, and little or no information is available for tanks with minimal boiloff rates for extended periods followed by high removal rates over a short period of time. Resupply operations present another area of further difficulty with cryogenic storage. The techniques and equipment required to satisfactorily transfer cryogenic fluids, or vessels containing cryogenic fluids, from resupply vehicles have not been developed and there appear to be some areas which may present some major difficulties.

4.2.2.1 High-Pressure Storage of Atmospheric Constituents

Figure 4-3 shows schematically the hardware and controls needed for a typical high pressure gas storage system. The design criteria given in Table 4-5 and data from References 4-7 through 4-9 were used as the basis in obtaining storage weights and volumes. These criteria are the best consensus of current practices and designs in the areas of materials, heat treatment, operating pressures, and manufacturing considerations. The information from Reference 4-9 indicates that with tank properties as specified in Table 4-5 the ratio of total spherical tankage weight to fluid weight is a function of only the fill pressure. For the fill pressures in Table 4-5, the storage weight (gas plus tank) are plotted in Figure 4-4.

The data from Reference 4-8 for spherical tankage specific volumes as a function of fill pressure were used to obtain the curves in Figure 4-5. Tank diameters can be limited by space available and number of tanks may be related to redundancy requirements. The total gas storage weights can be used in conjunction with Figure 4-5 to determine optimum weights.

Cylindrical tank characteristics are given in Figures 4-6 and 4-7. These data are used in conjunction with Figures 4-4 and 4-5. The curves in Figure 4-6 were developed from Reference 4-8 which recommends a value of 1.732 as the ratio of cylindrical to spherical tank wall thickness. When cylindrical tanks are used, two of the three variables, tank diameter,

Table 4-5

HIGH-PRESSURE GAS TANKAGE DESIGN DATA

	Oxygen	Nitrogen	Helium
Material	4340 Steel	Titanium alloy Ti-6Al-4V (TI C-120AV)	Titanium alloy Ti-6Al-4V (TI C-120AV)
Factor of safety	1.67	1.67	1.67
Fill pressure at cabin ambient, kg/cm^2	528	528	422
Weight of controls kg	2.25	2.25	2.25

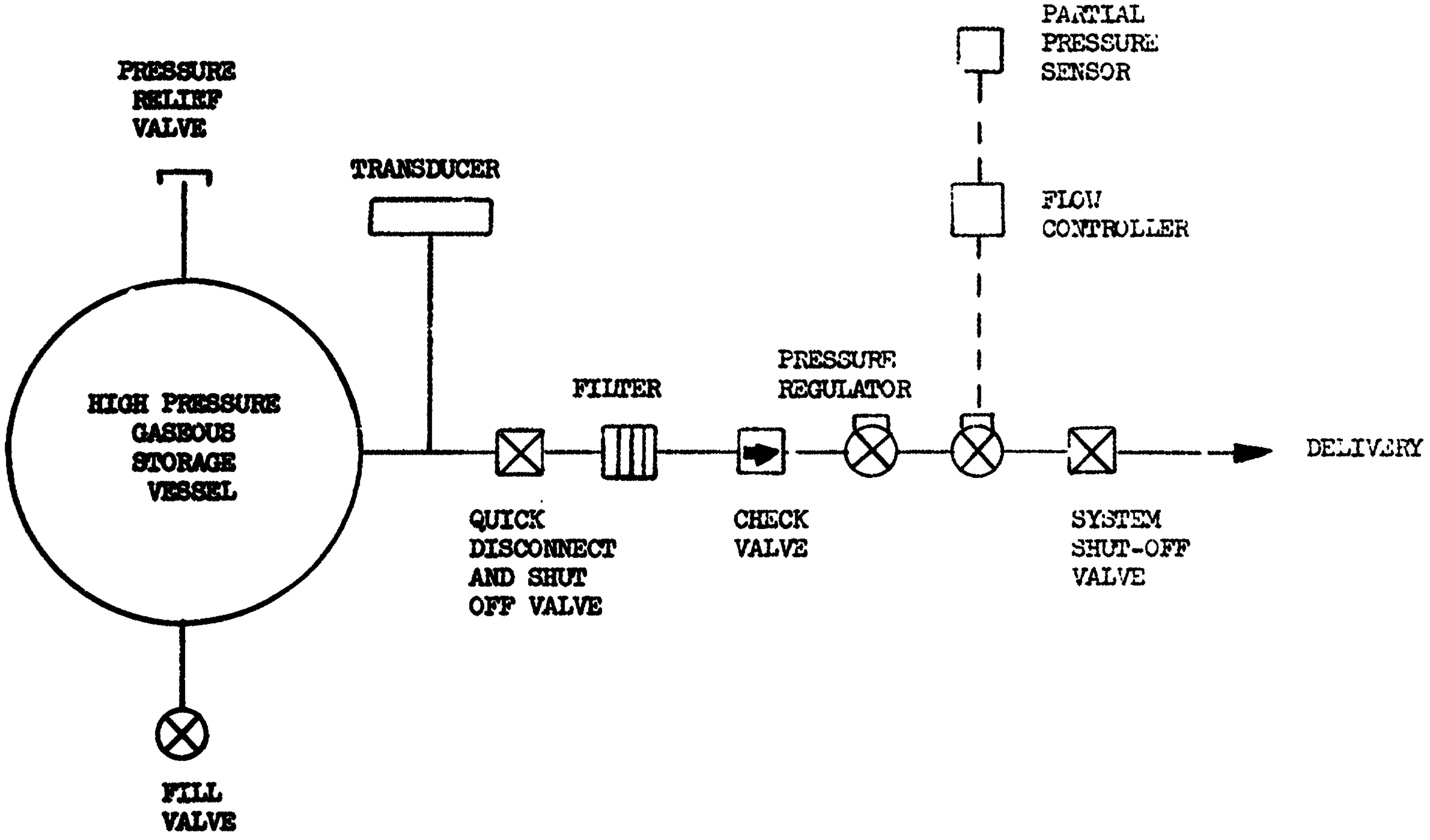


Figure 4-3. High-Pressure Gaseous Storage System

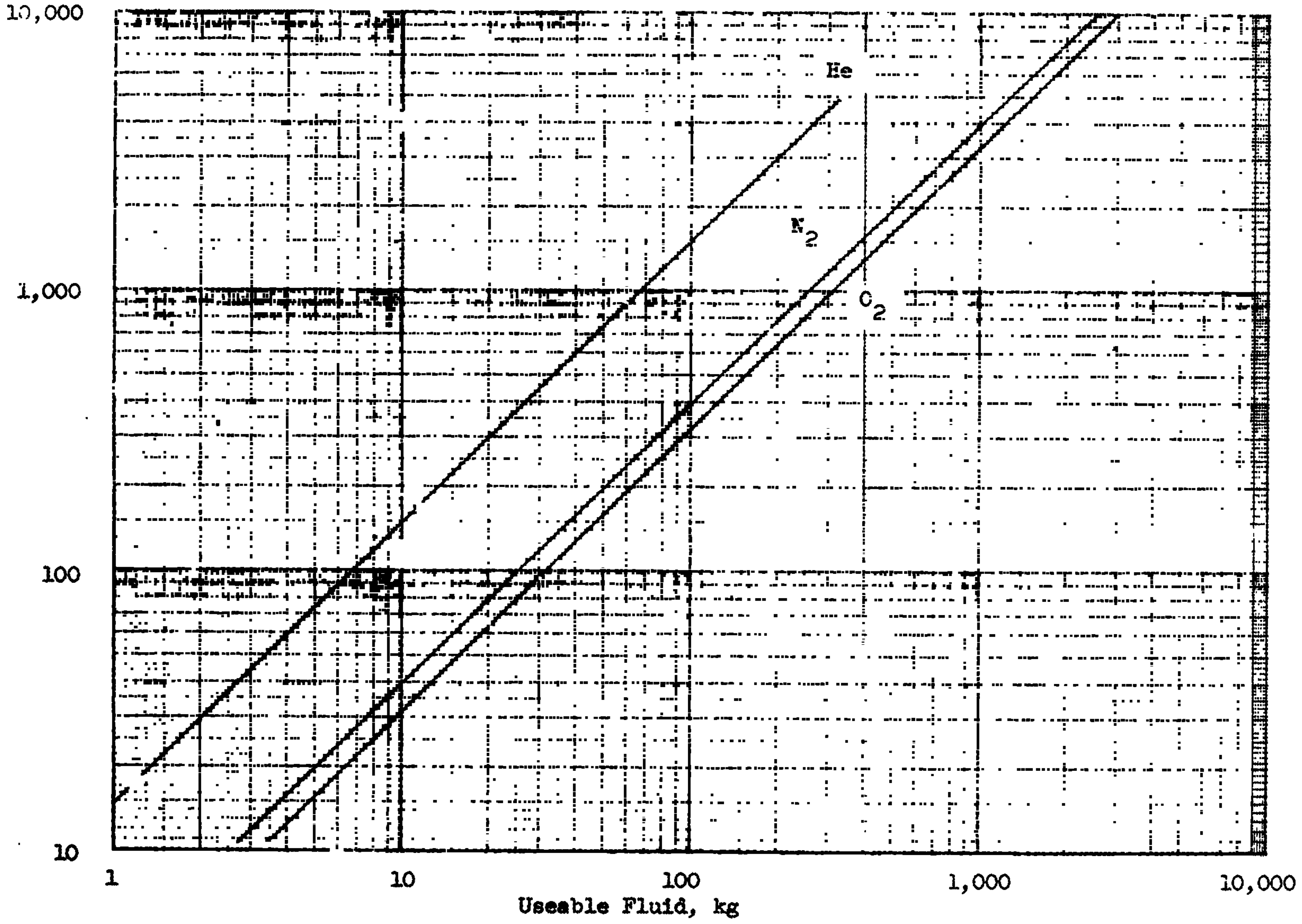


Figure 4-4 High-Pressure Gaseous Storage Weight

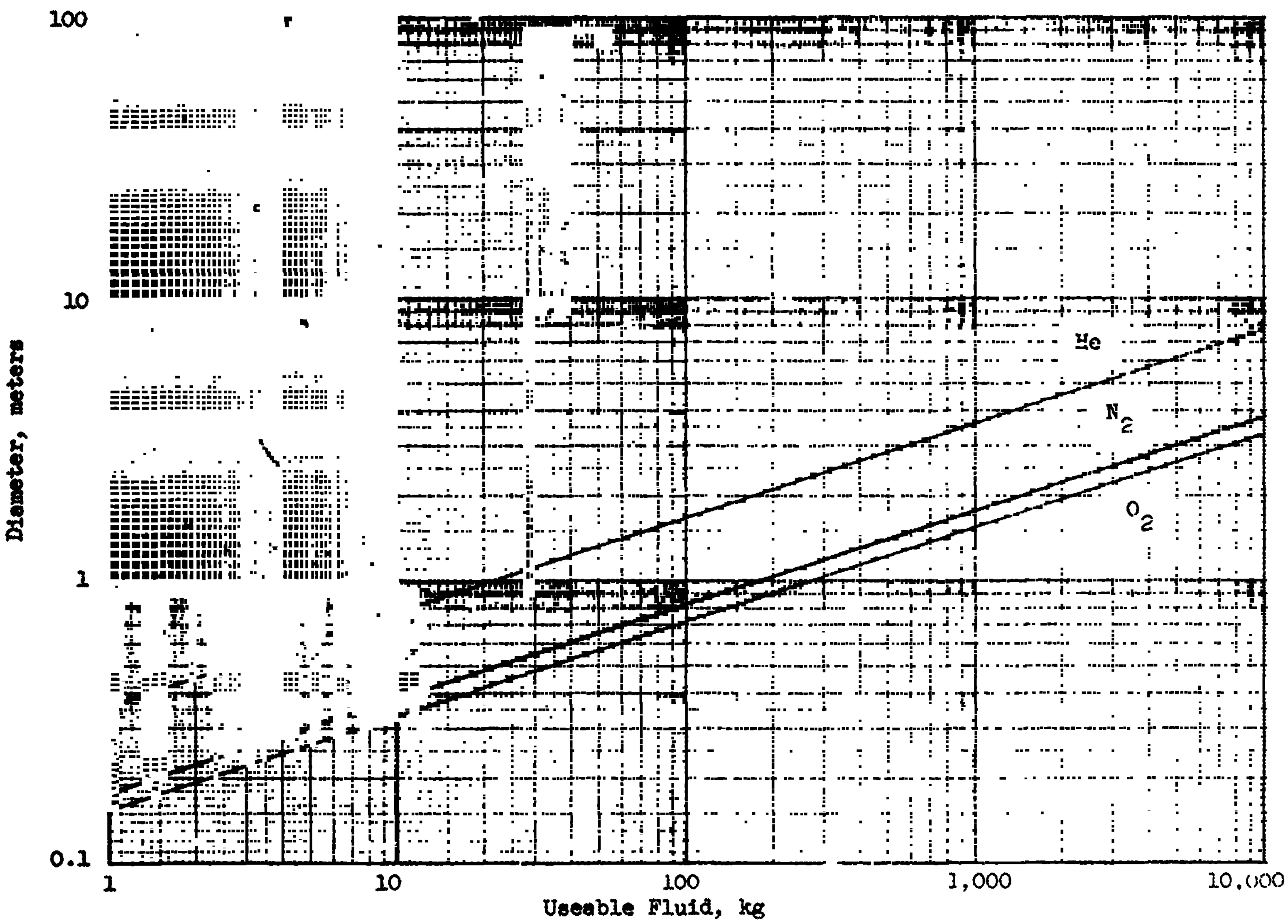


Figure 4-5. Outer Shell Diameter of High-Pressure Gaseous Spherical Storage Vessels

NOTE: Cylindrical Vessels Have Hemispherical Ends

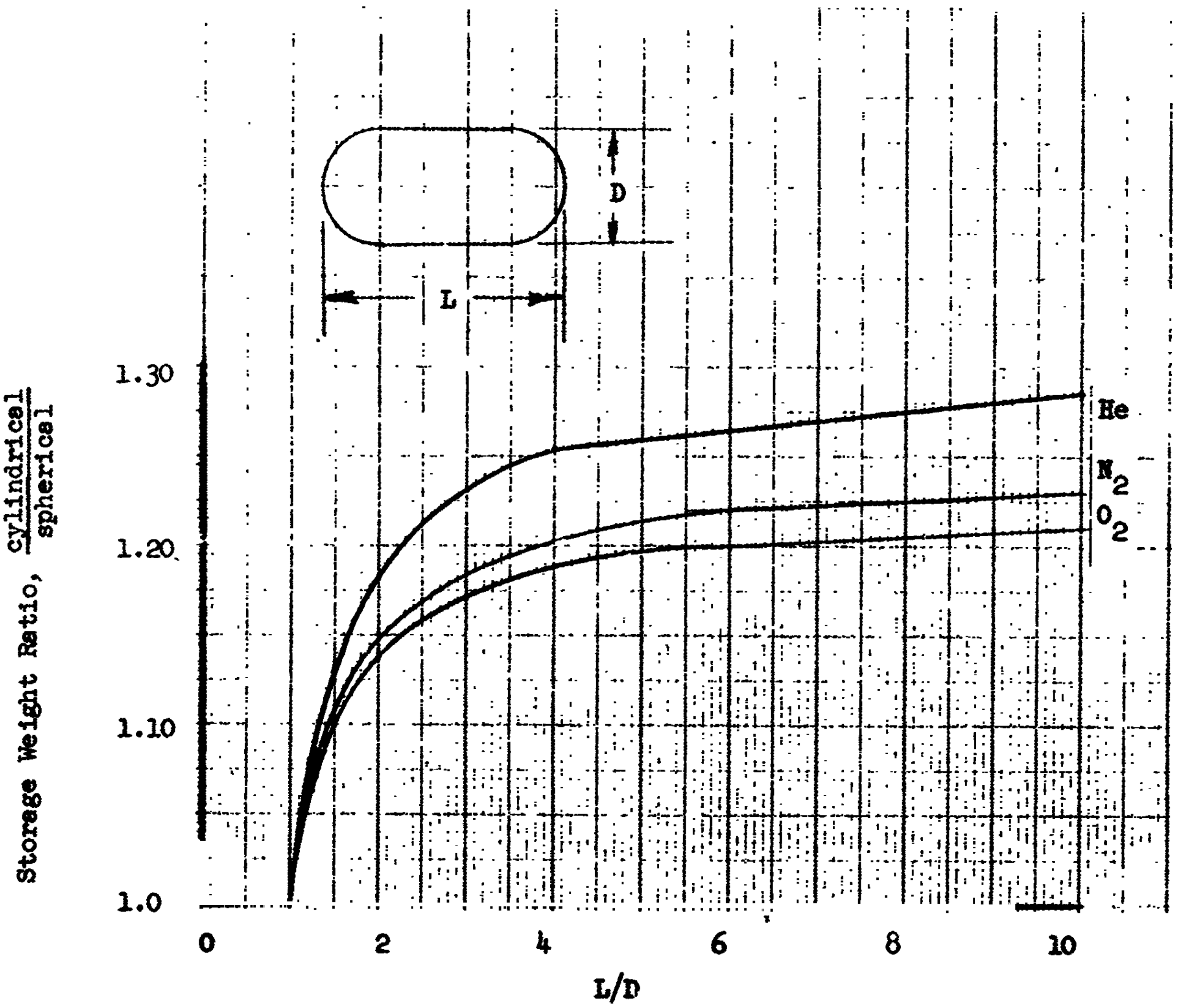


Figure 4-6. Ratio of Cylindrical to Spherical Weights of Storage Tanks for Equivalent Amounts of High-Pressure Gas

NOTE: Cylindrical Vessels Have Hemispherical Ends

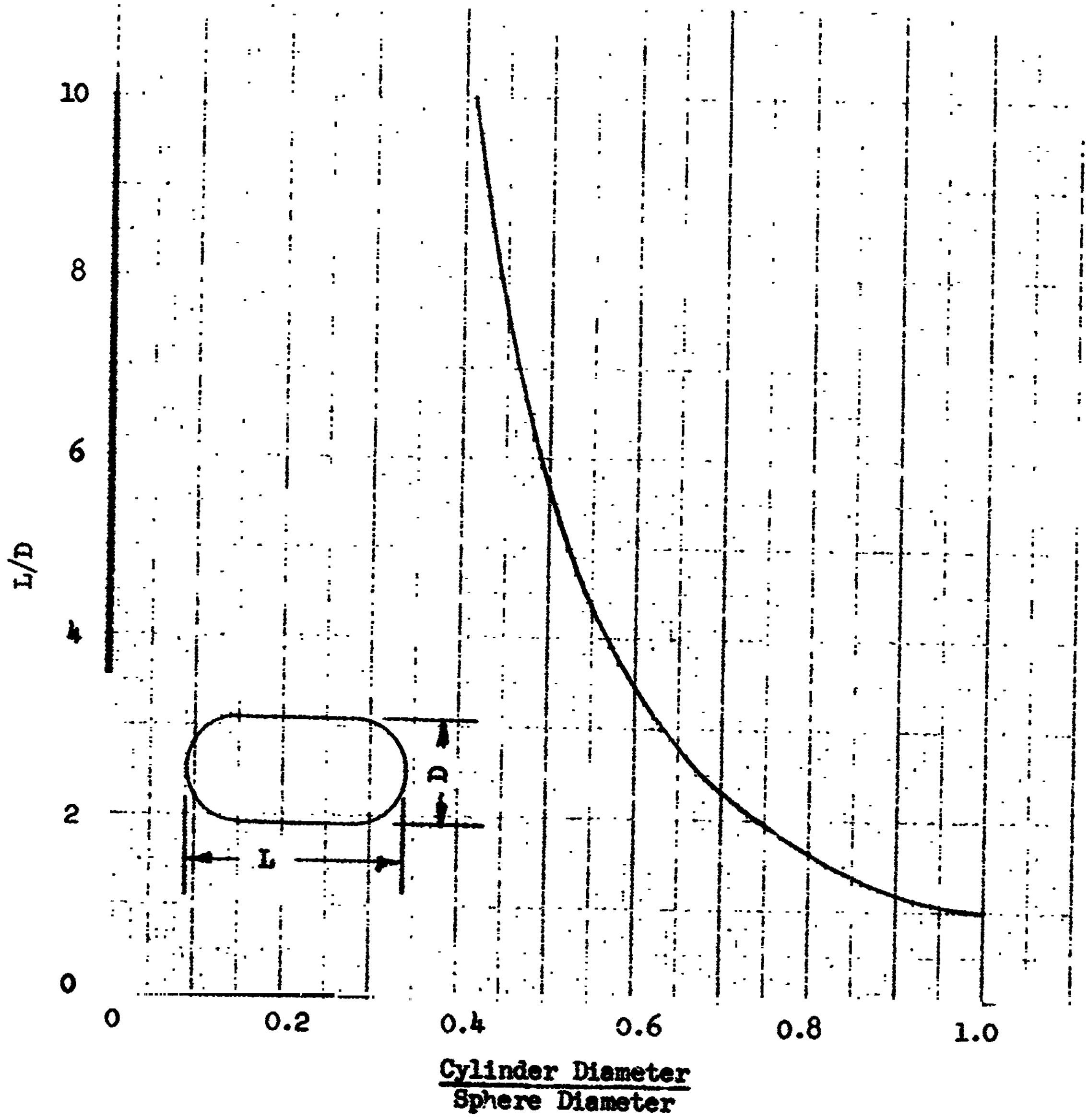


Figure 4-7. Size and Shape of Cylindrical Vessels and Spherical Vessels for Equal Volume

number of tanks, or tank L/D must be specified. The procedures used to determine the value for the unspecified member of these three variables and the weight of the tankage all include determinations of equivalent spherical tankage weight and diameter as intermediate steps. As indicated in Reference 4-7, high-pressure storage vessel control systems weigh approximately 4.5 kg for each pair of storage vessels. Since the controls are largely separately associated with each vessel, it is assumed for this study that the controls weigh 2.25 kg for each vessel.

4.2.2.2 Cryogenic Storage of Atmospheric Constituents

Supercritical storage tanks are first filled with subcritical fluid. The vessel is capped and the fluid is allowed to heat to a temperature higher than critical. The fluid then exists at a single-phase, homogeneous state at supercritical temperature and pressure. Fluid can be subsequently withdrawn from the tank at a constant pressure if heat is added. The required heat input, q, to the fluid at constant pressure, p, is given by the following relationship

$$q = w \; \rho\left(\frac{dh}{d\rho}\right)_p$$

where w is the fluid weight, ρ is the density, and h is the enthalpy. The above function has a minimum value of q for a given withdrawal rate. The insulation thickness is designed for this minimum amount of heat input which is termed the "design heat leak." At other withdrawal rates additional required heat is obtained from an electrical heater in the vessel. Supercritical storage tanks are usually designed for a maximum pressure of about 10 kg/cm^2 above the gas critical pressure to insure single-phase operation. The design criteria for cryogenic tanks are given in Table 4-6.

The major factors that affect the design of helium supercritical storage tanks are the very low temperatures and the lower mass flow of fluid normally required. Because of the combined effect of a very low critical temperature with possible higher heat leak and lower use rate, practical tank designs result in relatively high pressurization of the helium. To reduce this pressure it would require great amounts of insulation. Design data for helium tanks are given in Table 4-6.

Table 4-6

CRYOGENIC STORAGE TANK DESIGN DATA

	Oxygen	Nitrogen	Helium
Material			
Inner Tank (safety factor =2.0)	Inconel 718	Titanium 5 AL-2.5SN	Titanium 5 AL-2.5SN
Outer tank (safety factor =3.0)	Aluminum(1) alloy 2219	Aluminum(1) alloy 2219	Aluminum(1) alloy 2219
Insulation (2)	Vapor cooled shields and foils	Vapor cooled shields and foils	Vapor cooled shields and foils
Storage pressure (kg/cm^2, abs.)			
Supercritical (maximum)	62	42.1	212
Operating range	50 to 60	30 to 40	140 to 210
Subcritical	8.8	8.8	8.8
Supercritical storage temperature, °K	288	288	-
Weight of controls $(\frac{kg}{Tank})$			
Supercritical	6.35	6.35	6.35
Subcritical	3.62	3.62	3.62

---

(1) Monocoque construction

(2) Inner shell supported by outer shell through laminated fiber glass pads located at 90° increments on spherical sections and equivalent spacing on cylindrical section. Support loading of 8.08 cm^2/lb storage. Gap of 0.95 cm between outer foil and outer shell for lines and other miscellaneous items. Line heat leak = 0.146 W.

Subcritical tanks are filled in the same fashion as supercritical tanks; however, the operating pressure is then kept as low as practical to minimize vessel weight. As vapor is withdrawn from the tank, heat must be added to vaporize a like amount of remaining liquid. Consequently, the insulation thickness is determined by the heat of vaporization required to maintain the design delivery rate. Higher delivery rates require addition of electric power through the resistance heater. Lower delivery rates mean that the gas boiloff is lost by venting. The subcritical tanks have been assumed to operate at 8.8 kg/cm^2 maximum.

The material and factors of safety specified in Table 4-6 are representative of current designs and manufacturing methods. The inner shell materials are selected on the basis of high strength to weight ratios and high impact strength at cryogenic temperatures. The outer shell material is selected from a low weight criterion (Reference 4-8). The properties of the thermal insulation and additional design details for a given cryogenic tank type are usually proprietary vendor data. Vapor cooled shields are often included in the insulation assembly to reduce insulation thickness for this permits fluid leaving the storage vessel to intercept part of the heat entering the tank through the vessel outer shell. Insulation assemblies including these shields are lighter than assemblies without shields when use rates are relatively low.

Figure 4-8 shows the controls and auxiliary hardware for a supercritical fluid storage tank. The weight of this associated equipment has been estimated at 6.3 kg (Reference 4-9). The weights of spherical supercritical tanks for oxygen, nitrogen, and helium are given in Figures 4-9 through 4-11. Supercritical spherical tank diameters are given in Figure 4-12.

The schematic for a two-phase cryogenic storage system with vapor delivery is shown in Figure 4-12. This associated auxiliary hardware for each tank has been estimated at 3.62 kg (Reference 4-9). The physical characteristics for subcritical oxygen and nitrogen spherical tanks are shown in Figures 4-14 through 4-16.

Figures 4-17 and 4-18 show weight ratios of cylindrical tankage compared to spherical tankage versus L/D for supercritical and subcritical storage,

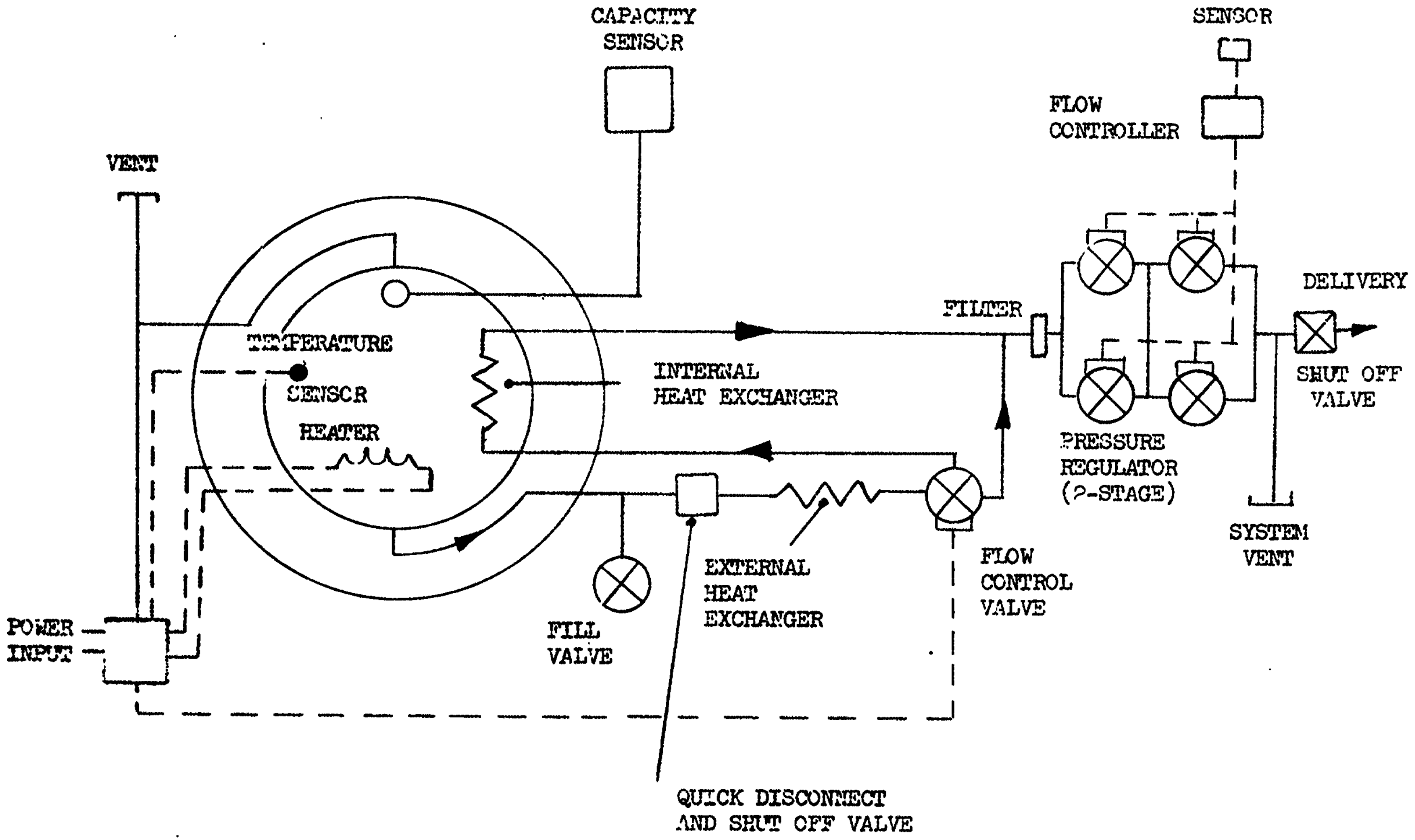


Figure 4-8. Supercritical Storage System

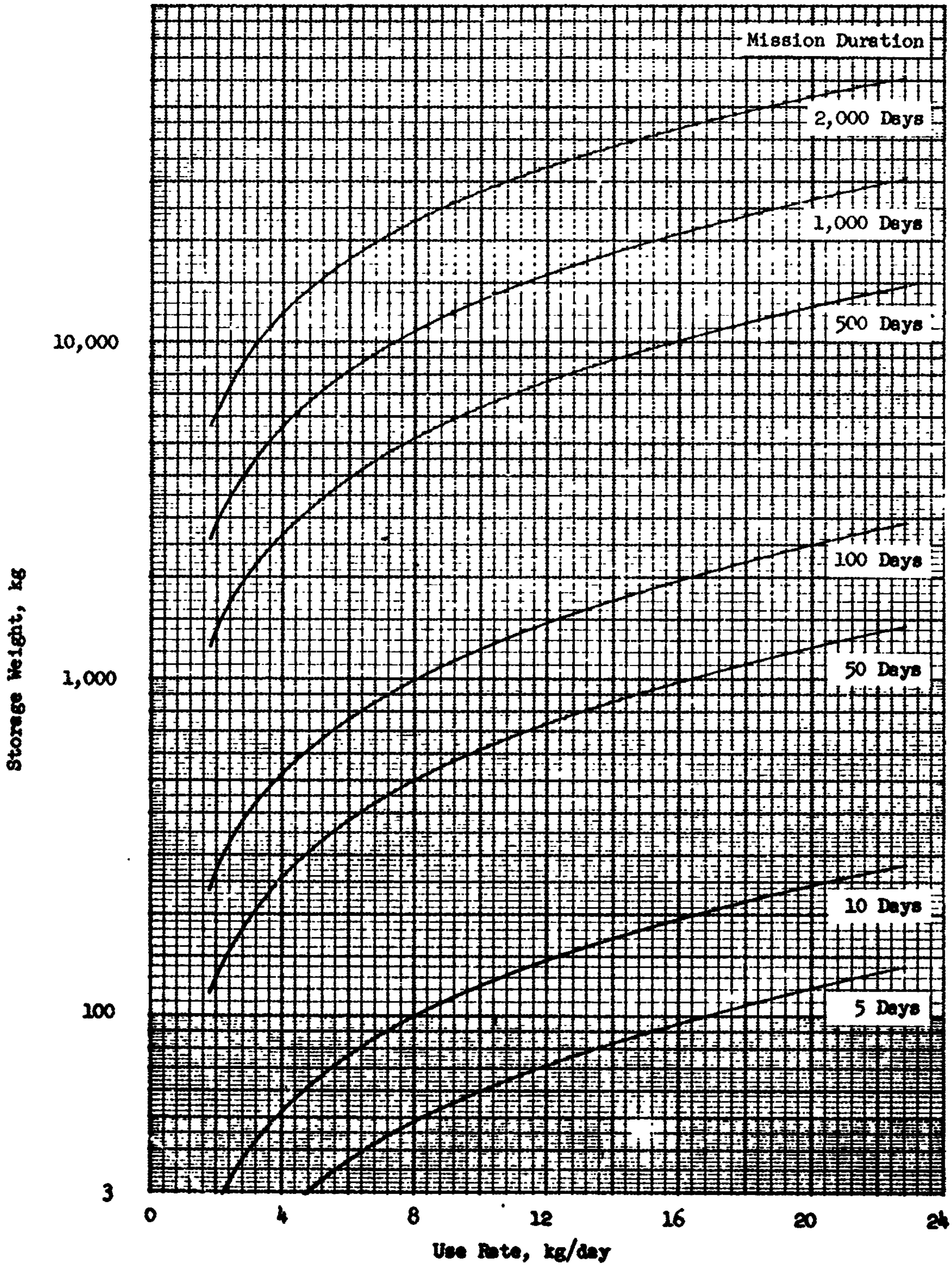


Figure 4-9. Supercritical Oxygen Spherical Storage Weight

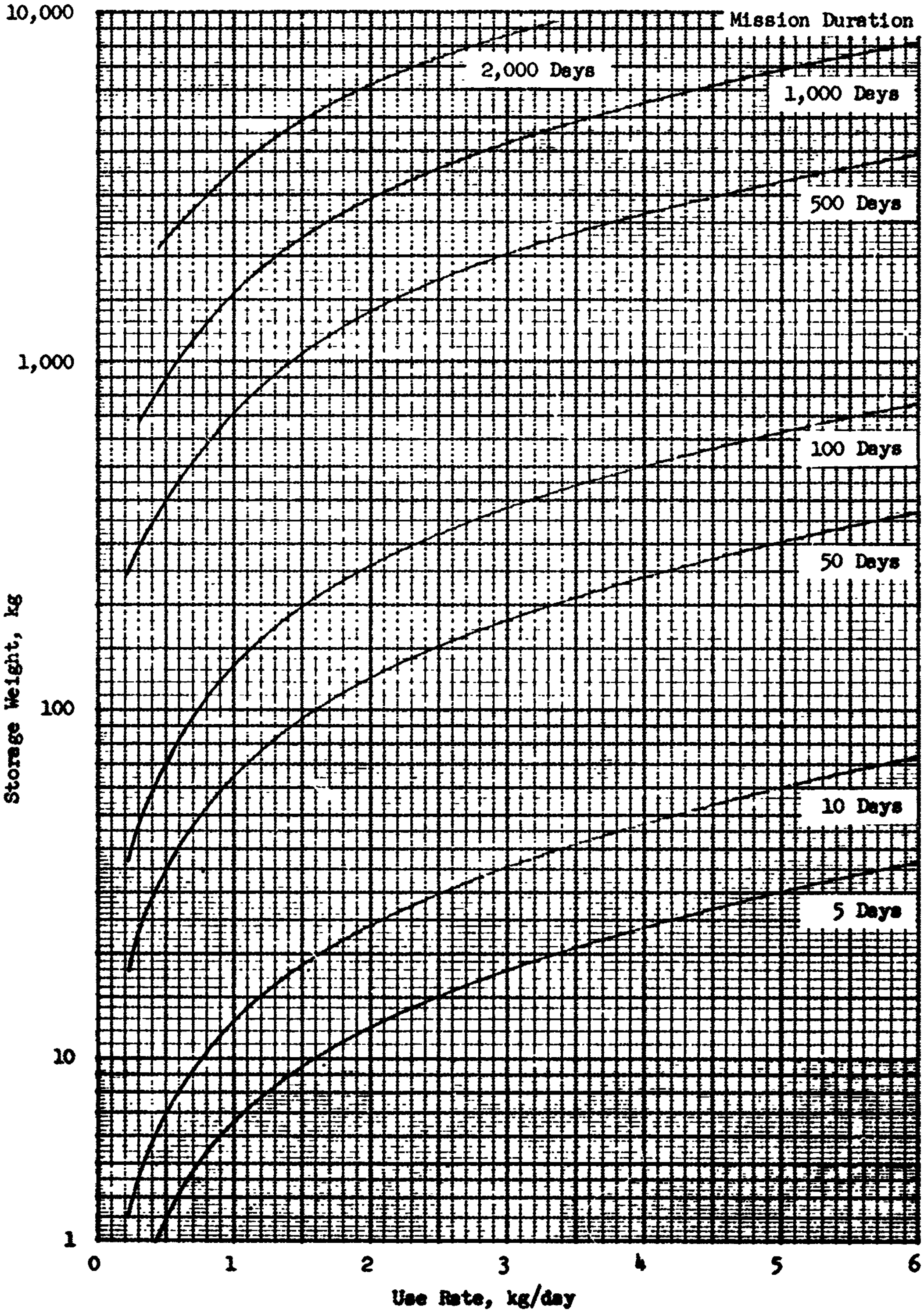


Figure 4-10.: Supercritical Nitrogen Spherical Storage Weight

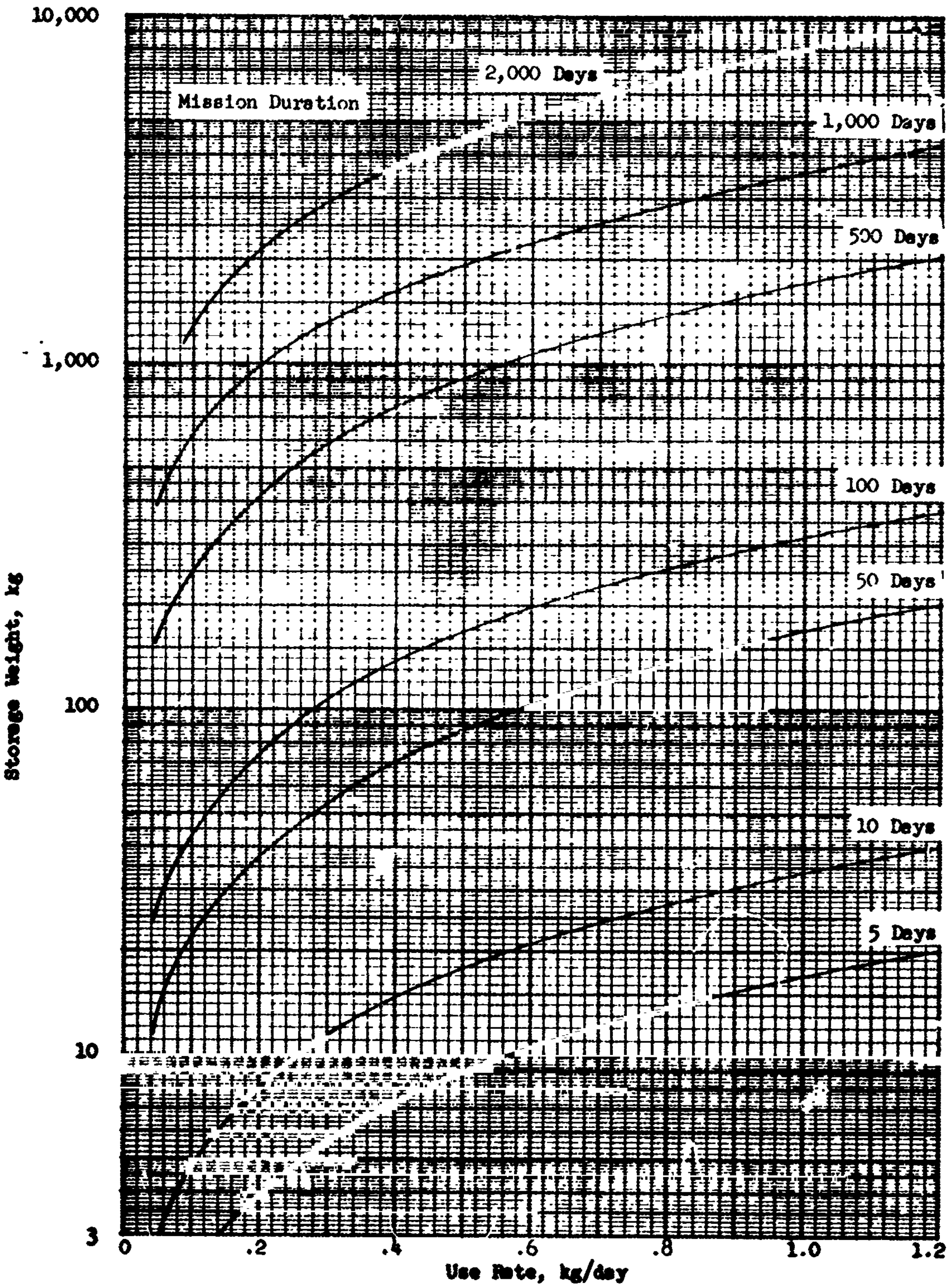


Figure 4-11. Supercritical Helium Spherical Storage Weight

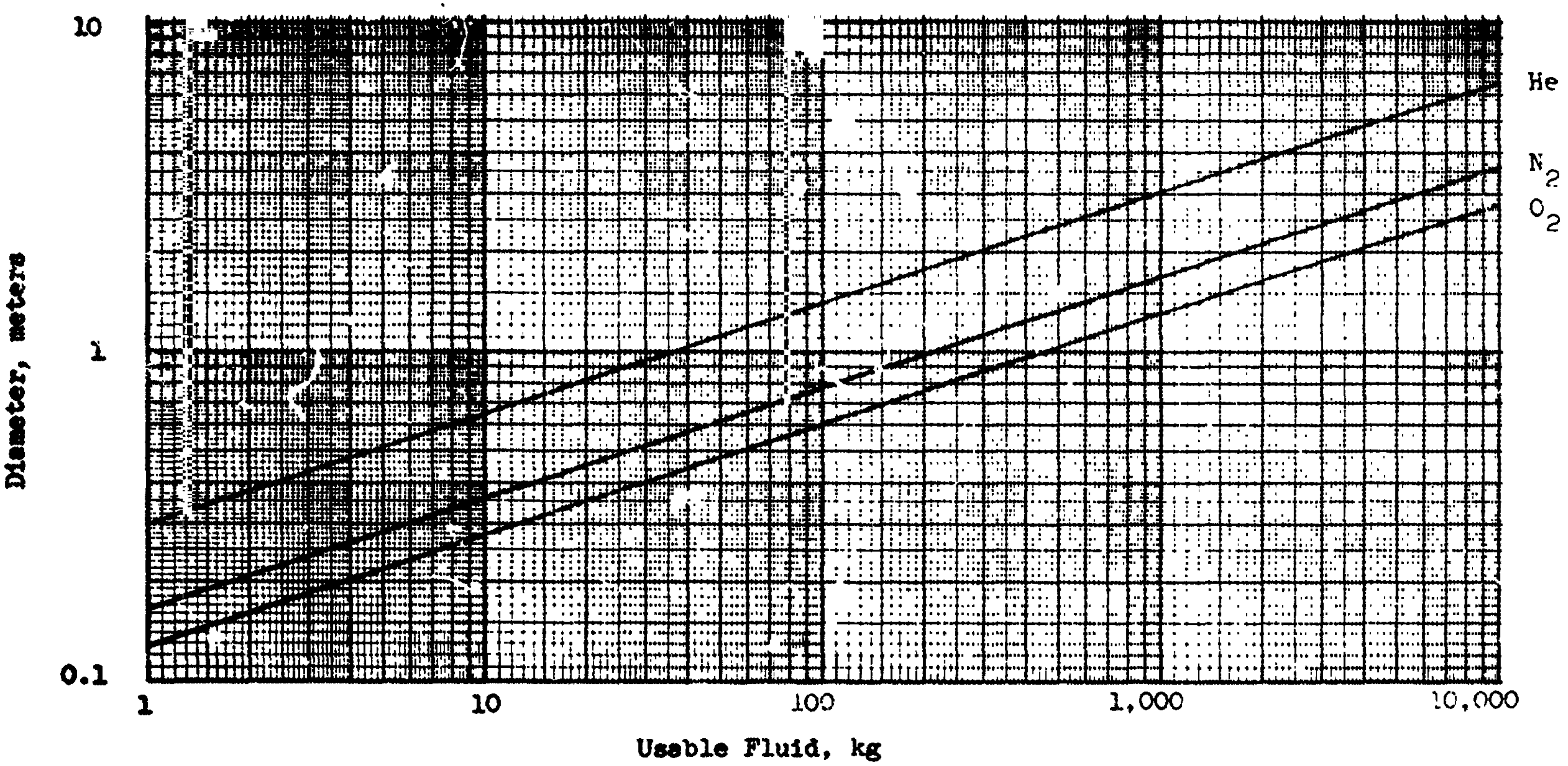


Figure 4-12. Outer Shell Diameter of Supercritical Fluid Spherical Storage Vessels

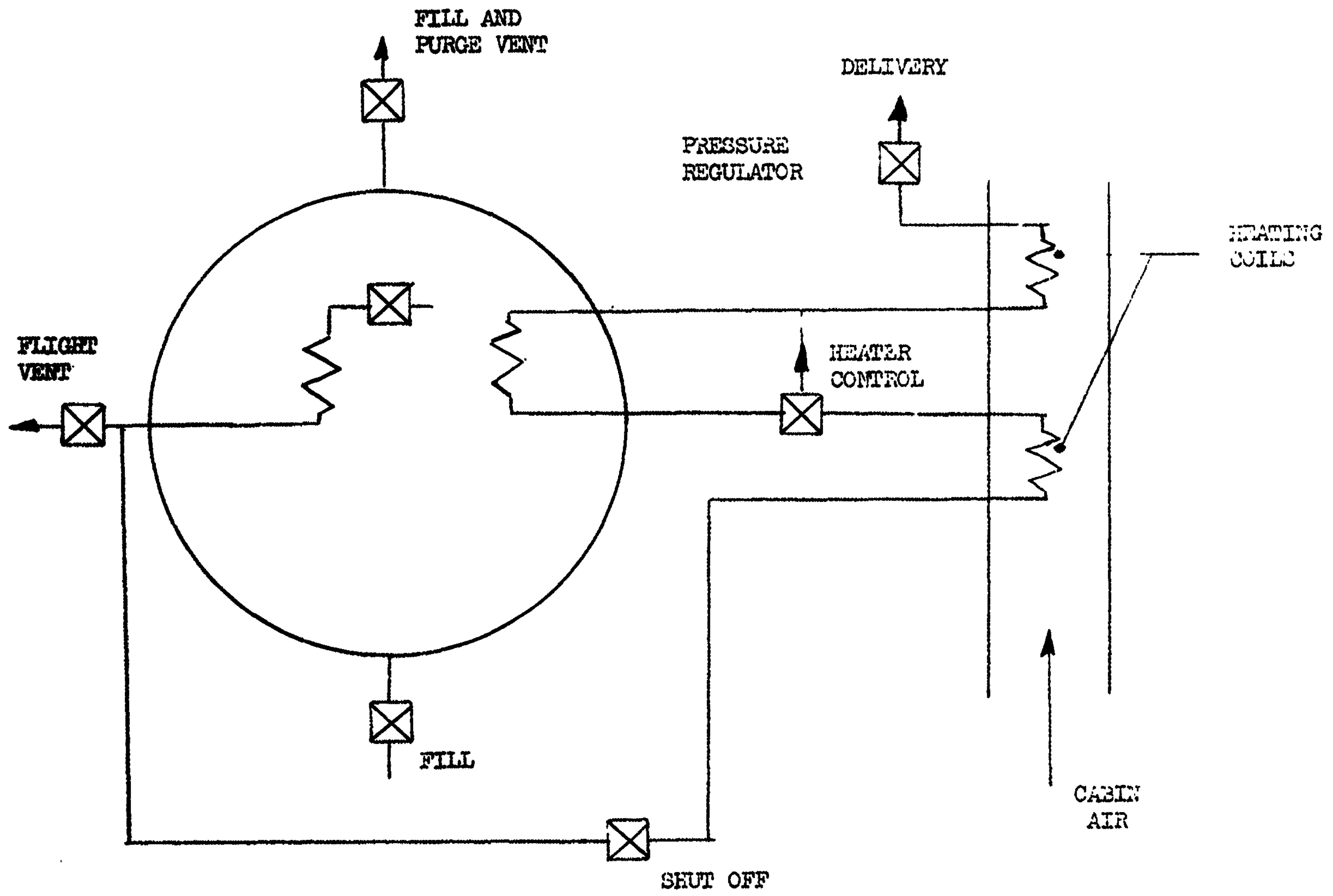


Figure 4-13. Subcritical Storage System

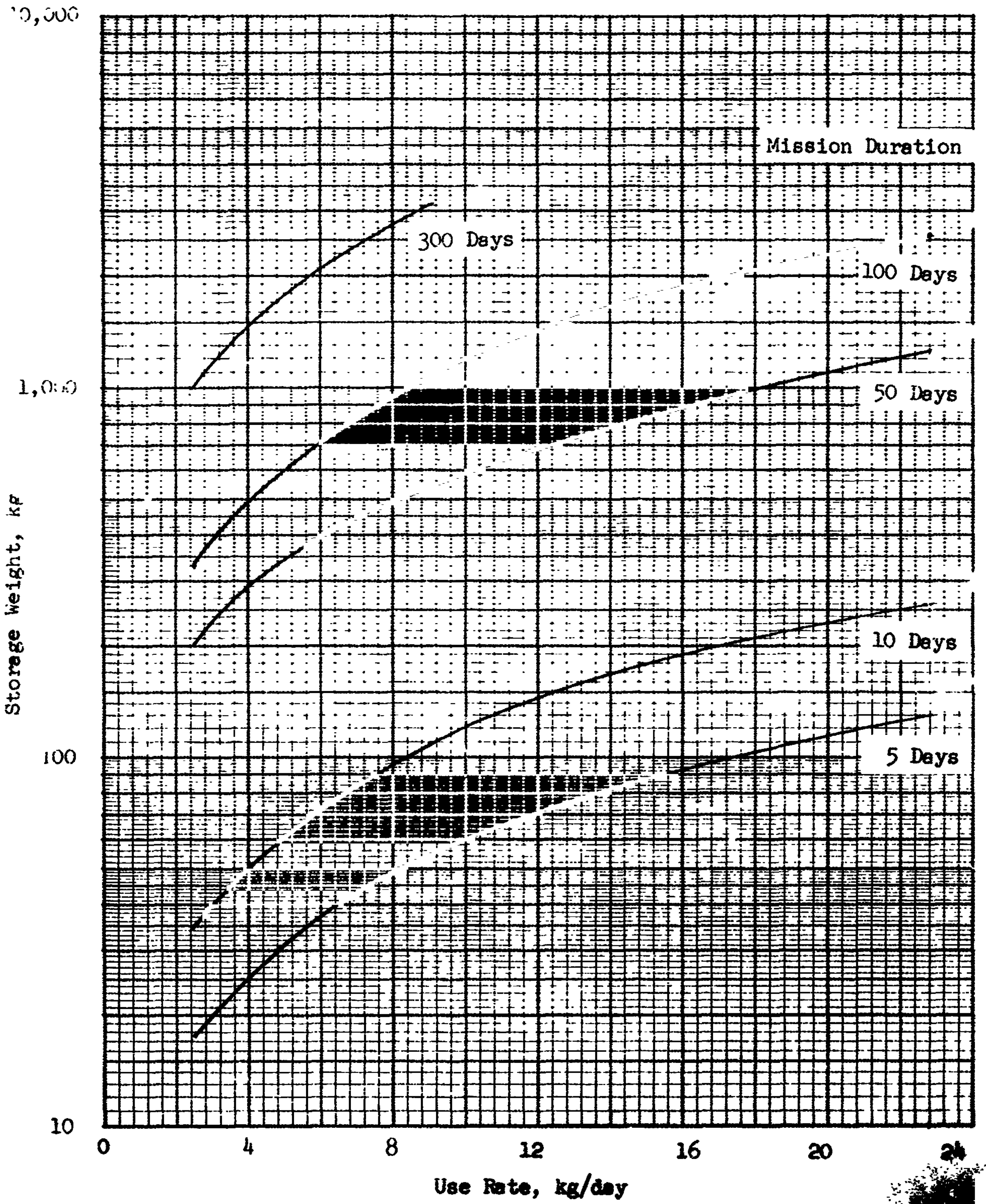


Figure 4-14. Subcritical Oxygen [illegible]

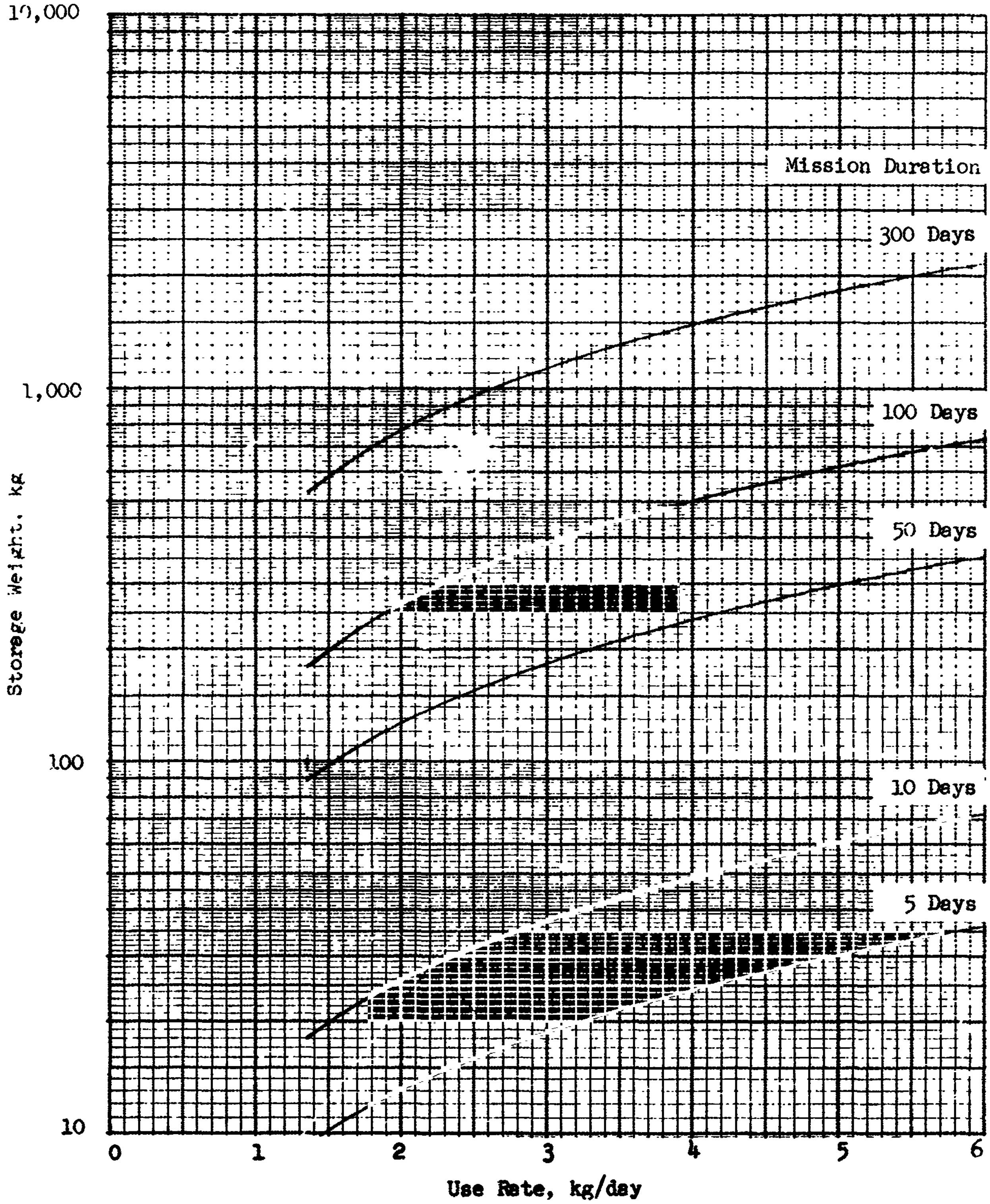


Figure 4-15. Subcritical Nitrogen Spherical Storage Weight

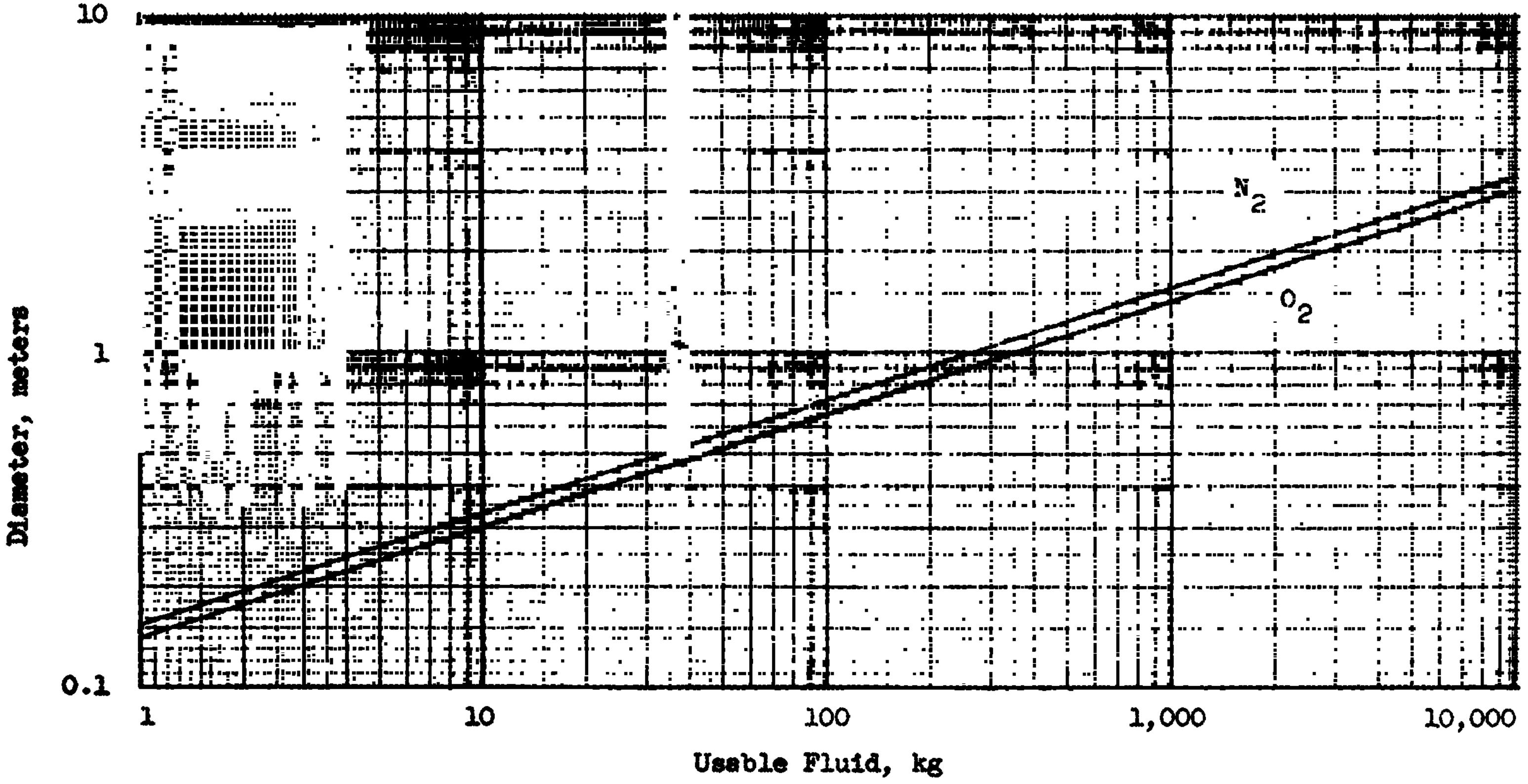


Figure 4-16. Outer Shell Diameter of Subcritical Fluid Spherical Storage Vessels

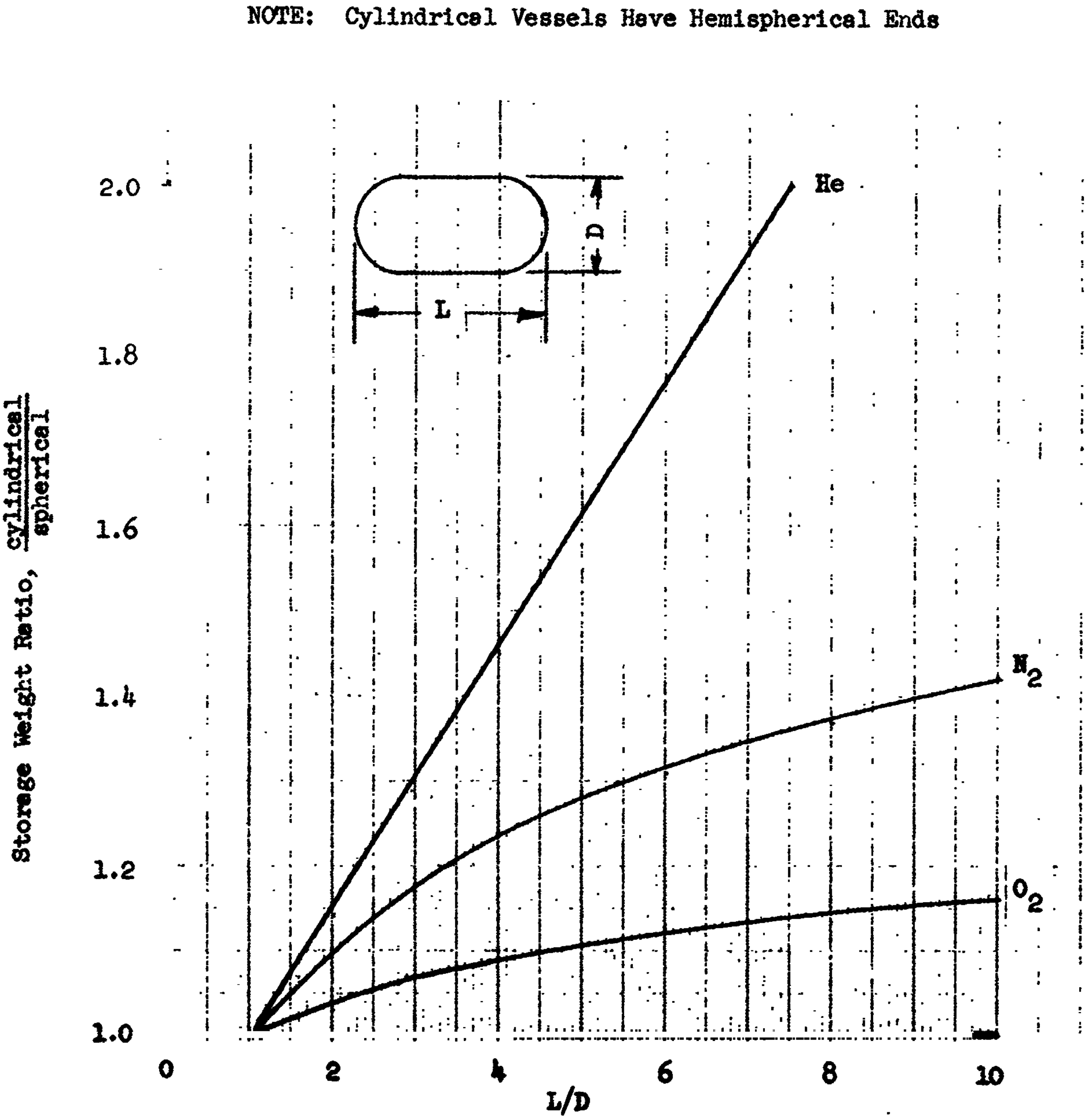


Figure 4-17. Ratio of Cylindrical to Spherical Storage Weights, Vessel and Fluid, for Equivalent Amounts of Supercritical Fluid

NOTE: Cylindrical Vessels Have Hemispherical Ends

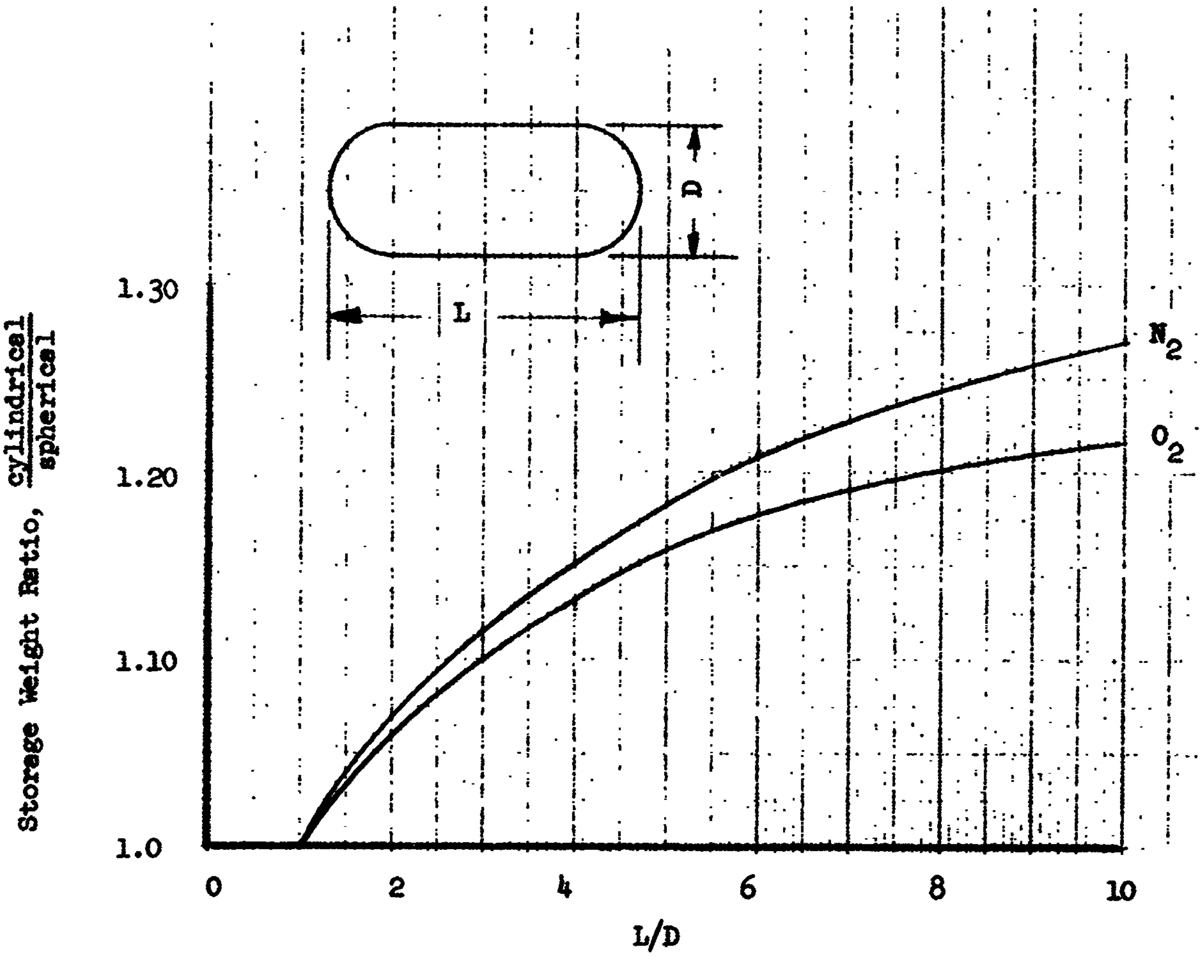


Figure 4-18. Ratio of Cylindrical to Spherical Storage Weights, Vessel and Fluid, for Equivalent Amounts of Subcritical Fluid

respectively. These data were obtained analytically from spherical tankage data by imposing the following assumptions:

1. The outer shell structural sizing same as for spherical of same diameter (Reference 4-8).
2. The ratio of three to two between cylindrical and spherical inner shell wall thicknesses (Reference 4-8).
3. Equivalent surface areas for cylindrical and spherical tanks were used to scale insulation weights to provide uniform percentage use rates throughout the vessels.

Two of the three variables of number of tanks, tank diameter, or tank L/D, must be specified when cylindrical tankage is indicated. The parametric data in Figures 4-9, 4-10, 4-11, 4-12, and 4-17, and in Figures 4-14, 4-15, 4-16, and 4-18 may be used to determine supercritical or subcritical storage tank requirements, respectively. The procedures require the determination of the spherical tankage data as an intermediate step to the cylindrical tank determinations.

Peak power requirements at various gas flow rates for supercritical and subcritical storage are shown in Figure 4-19. Reasonable estimates of the average power are equivalent to one-half the values shown in Figure 4-19. Figure 4-20, showing the simple relationship between diameter and volume, can be used to facilitate tankage space requirement determinations.

4.2.3 Oxygen Recovery

The necessary equipment to accomplish oxygen recovery typically includes several individual components such as chemical reactors, regenerative heat exchangers, blowers, dehumidifying condensers, filters, electrochemical cells, pumps, and controls. At the present stage of development of oxygen recovery units, the emphasis is mainly directed toward achieving workable systems and also satisfying the general constraints imposed by space vehicle requirements of compactness, light weight, low power requirement, compatibility with low gravitational fields, low maintenance requirements, and compatibility with other portions of life support subsystems.

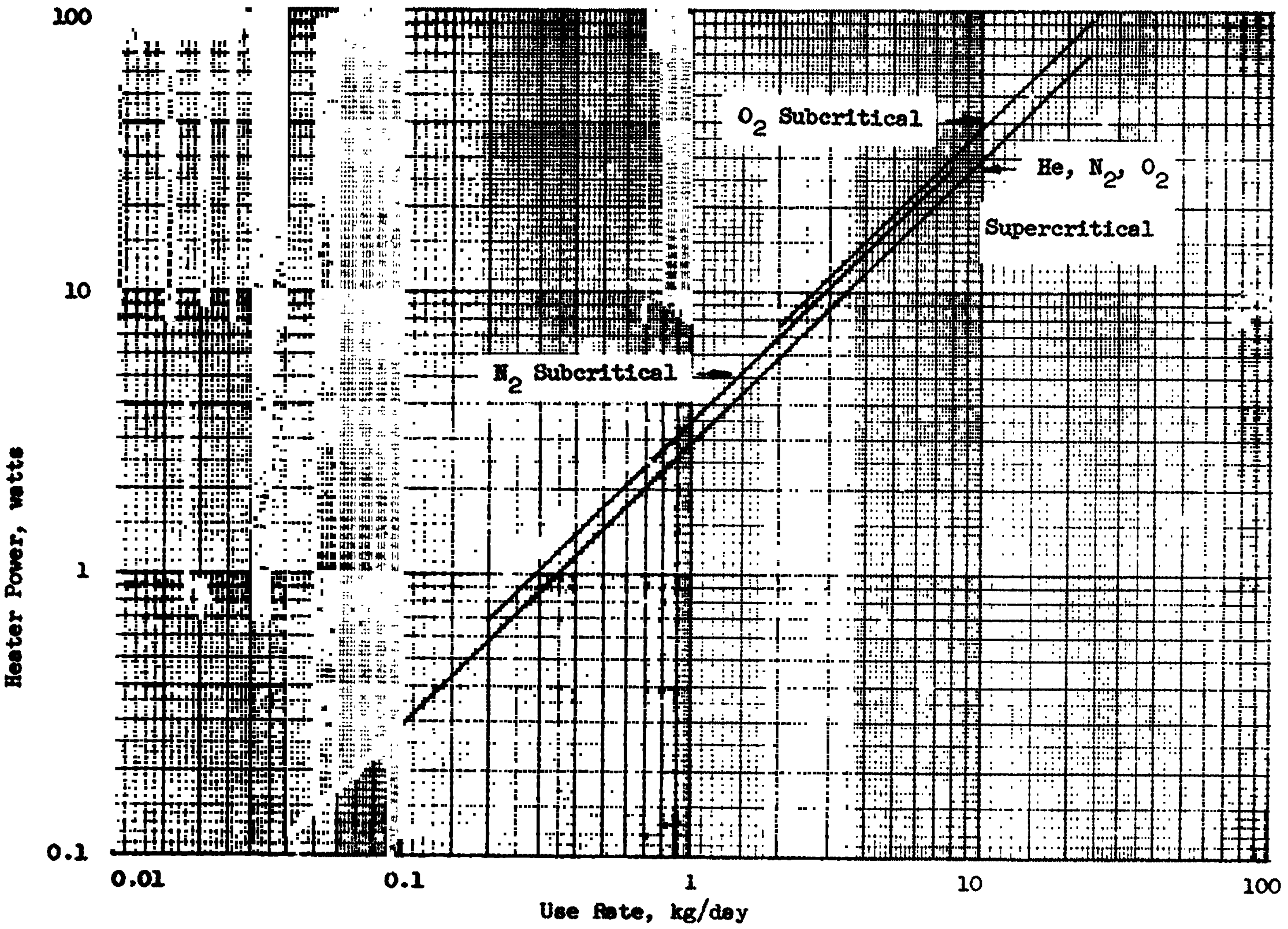


Figure 4-19. Cryogenic Storage Peak Power Requirement

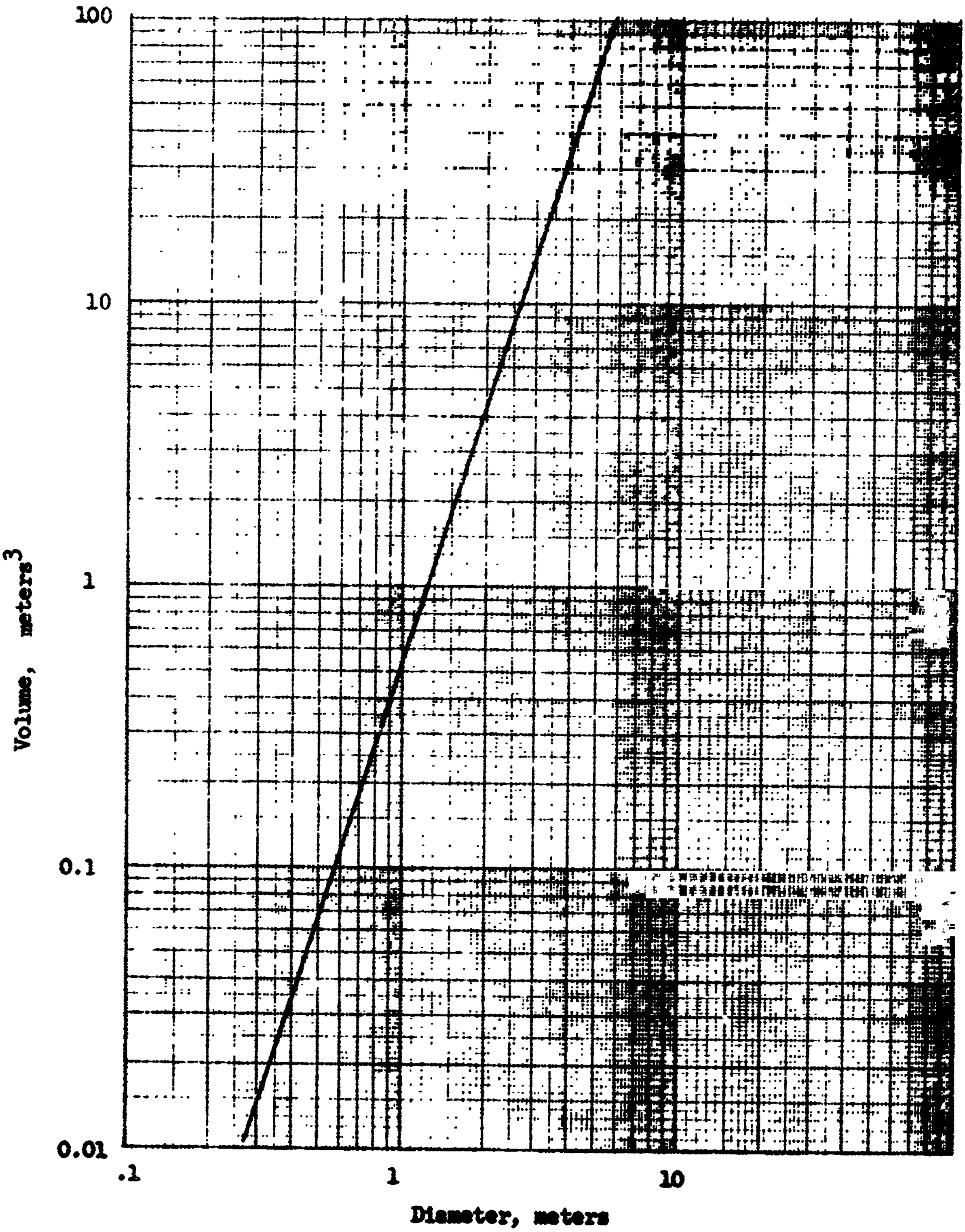


Figure 4-20. Diameter-Volume Relationship for Spherical Vessels

In the course of this study, the oxygen recovery methods for which scaling laws were developed include the following:

1. Bosch
2. Molten carbonate
3. Solid electrolyte
4. Sabatier with methane vent
5. Sabatier with acetylene vent
6. Sabatier with all hydrogen recovered

The electrolysis concepts for which scaling laws have been developed include:

1. Rotating cell with H_2-diffusion
2. Double membrane cell with H_2SO_4 electrolyte
3. Water vapor cell
4. Membrane cell with KOH electrolyte

Prototype units of some O_2 recovery methods are operating. Some of these prototypes have been used in earth-based manned tests of complete life support systems. In the case of other functional methods, laboratory models have been developed and sufficient experiments have been performed to determine feasibility and to delineate problem areas. In general, the equipment which accomplishes O_2 recovery has not reached a level of development where satisfactory operation is assured. Present development efforts are directed to reducing weight and power and increasing performance and reliability.

Figure 4-21 shows the alternate functional oxygen recovery methods considered in the study and the interfaces involved. The fundamental goal of water electrolysis was considered to be the generation of sufficient O_2 for human consumption, and the secondary goal was to generate sufficient H_2 for CO_2 reduction.

Because the oxygen recovery units work in a closed cabin, mass balance is required to enable the proper sizing of the associated equipment. A detailed discussion follows about the way in which the mass flow relates the various components that complete a given oxygen recovery method. This discussion is followed by detailed evaluations of oxygen recovery processes and

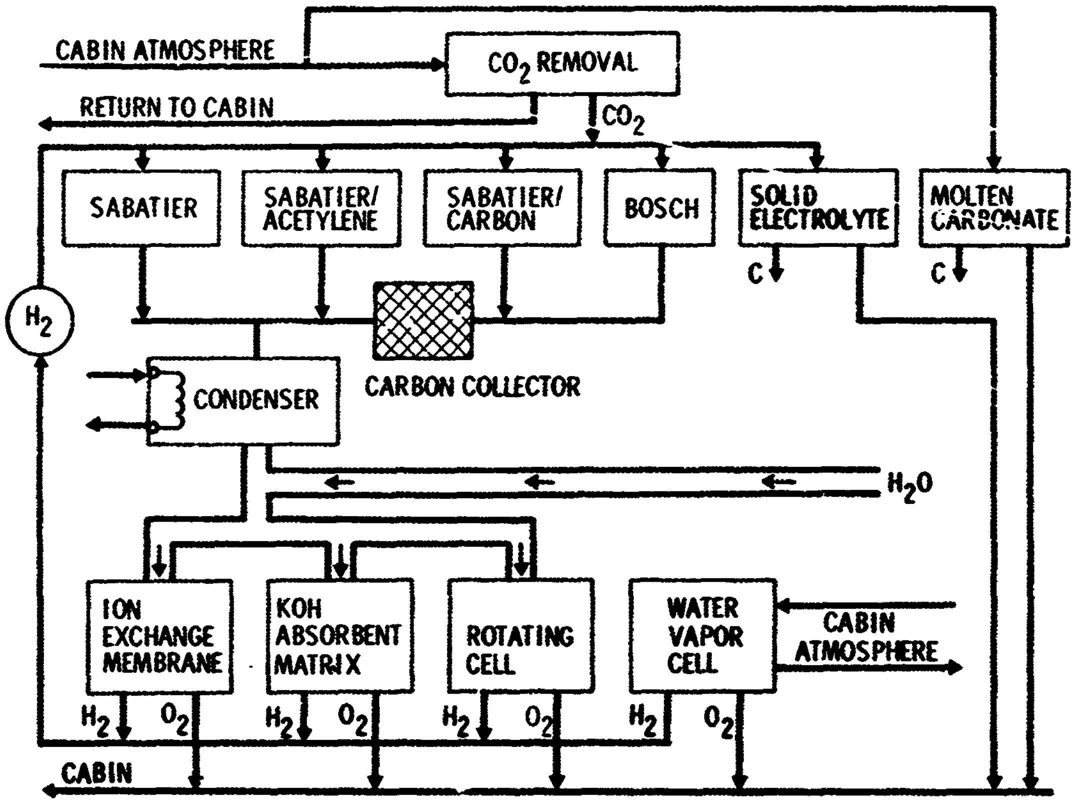


Figure 4-21. Alternate Oxygen Recovery Methods

electrolysis methods. The scaling laws and parametric relations are developed for each method in conjunction with the discussion.

4.2.3.1 Mass Flow and Balance Computations

A set of mass balance equations was established that followed the flow requirements indicated on Figure 4-21 and accommodated the various combinations of functional methods. Computational logic was prepared which followed the chemical processes to solve the mass balance equations and determine the flow rates for the various constituents. The usual procedure for O_2 recovery permits O_2 to be recovered from CO_2 by reduction of CO_2 with H_2 followed by electrolysis of the resulting water, or by the electrolysis of compounds formed from CO_2. Independent of the recovery unit, oxygen can be generated by electrolysis of water vapor in the cabin atmosphere by use of the water vapor electrolysis cell.

The water generated by CO_2 reduction is always considered to be available for use in the water electrolysis units. Other water sources include excess water from human metabolic processes, water recovery system, food generating processes, or stored water. The computational logic for the ACS permits the sources of water to be used in any combination. Deficits in cabin O_2 needs resulting from limited water electrolysis are assumed to be satisfied by stored O_2.

The computational logic permits a choice of one of six functional methods to reduce metabolically generated carbon dioxide. Mass flow arrangements show that the reduction methods fall into two categories and that one computational procedure may serve for all methods in a category. The six methods are classified as follows:

Category 1	Molten carbonate Solid electrolyte
Category 2	Sabatier - methane vent Sabatier - acetylene vent Sabatier - all hydrogen recovered Bosch

The computational procedure for the solid electrolyte or molten carbonate in Category 1 have a straightforward solution. The chemical reactions for both are identical and are written as:

$$CO_2 \longrightarrow C + O_2 \tag{4-1}$$

The equipment sizing scaling laws are in terms of CO_2 mass flow as the independent variable, these reduction devices are simply sized by using the net CO_2 available for O_2 recovery.

The computational procedures for Category 2 reactions are considerably more complicated because they involve several independent chemical reactions with broad ranges of efficiency. Figure 4-22 is a generalized mass flow diagram for Category 2 recovery methods. Table 4-7 gives a nomenclature for the symbols used in this diagram.

Inspection of the detailed mass balance equations for the four methods in Category 2 revealed that a single procedure could be used when correlating terms are applied to the individual processes. The development of a mass balance for the Sabatier-acetylene process which involves three reactions

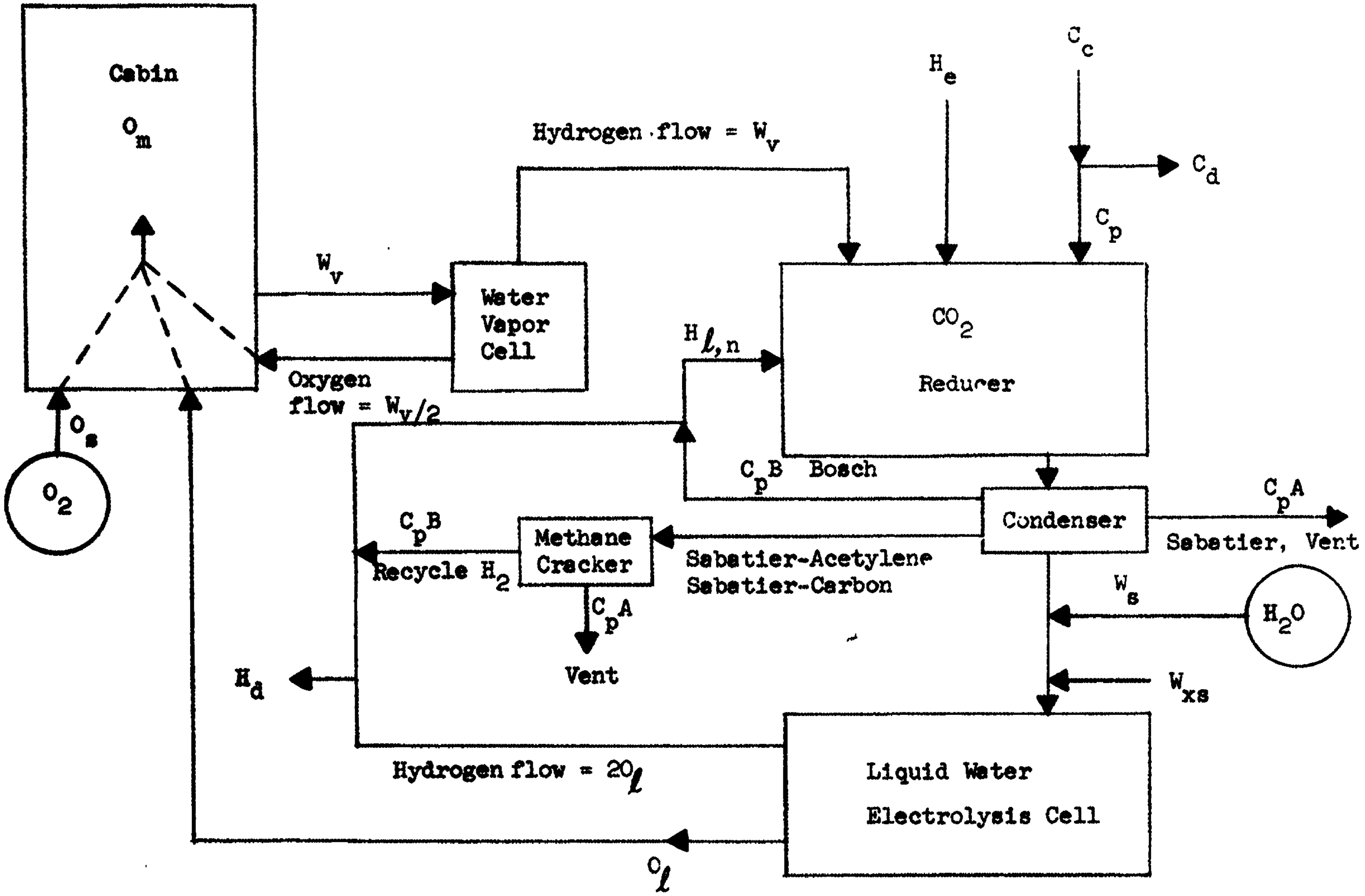


Figure 4-22. Generalized O_2 Recovery Flow Diagram for Category 2

Table 4-7

O_2 RECOVERY NOMENCLATURE

A - correlating parameter

B - correlating parameter

C_c - CO_2 supply rate - from CO_2 collection

C_d - CO_2 vent rate

C_p - CO_2 processing rate through reducer

H_d - H_2 dump rate

H_e - H_2 supply rate - from electrodialysis

$H_{\ell,n}$ - H_2 rate - net of dump, liquid electrolysis and recycle H_2 rates

O_ℓ - O_2 generation rate - liquid electrolysis

O_m - O_2 rate - total cabin makeup from sum of leak, airlock, food, electrodialysis, and metabolic rates

O_s - O_2 supply rate - gas storage

W_s - H_2O supply rate from stored water

W_v - H_2O rate - vapor electrolysis

W_{xs} - excess water rate option 3 on Table 4-10

η_c - methane cracker efficiency

η_r - CO_2 reduction reactor efficiency

η_w - electrolysis efficiency

is presented to illustrate the general procedure and rationale. The chemical formula relating the Sabatier reaction is as follows:

$$4.35H_2 + CO_2 \longrightarrow \eta_r CH_4 + 2\eta_r H_2O$$

$$+ 4(1 - \eta_r) H_2 + 0.35 H_2 + (1 - \eta_r) CO_2 \qquad (4\text{-}2)$$

All terms are molar flows and have units of kg-moles/hr. Experience with this reaction has shown that an additional 0.35 mole of H_2 for each mole of CO_2 above the stoichiometric ratio should be supplied.

The reaction for methane cracking is:

$$\eta_r CH_4 + 4(1 - \eta_r) H_2 + 0.35 H_2 \longrightarrow \frac{\eta_r \eta_c}{2} C_2 H_2 + \eta_r \eta_c \frac{3}{2} H_2$$

$$+ \eta_r (1 - \eta_c) CH_4 + 4(1 - \eta_r) H_2 + 0.35 H_2 \qquad (4\text{-}3)$$

For the electrolysis of water, assuming $\eta_w = 1.0$, then:

$$2\eta_r H_2O \longrightarrow 2\eta_r H_2 + \eta_r O_2 \qquad (4\text{-}4)$$

Relating the moles of hydrogen entering the CO_2 reactor to the moles of CO_2 processed, and using the nomenclature in Table 4-7.

$$H_{\ell,n} + W_v + H_e = 4.35 C_p \qquad (4\text{-}5)$$

Relating the moles of hydrogen entering the liquid electrolysis unit to the hydrogen generated,

$$2\eta_r C_p + W_s + W_{xs} = 2O_\ell \qquad (4\text{-}6)$$

Relating the hydrogen flow out of the liquid electrolysis cell and the methane cracker to the sum of the excess hydrogen dumped to space and the recycled hydrogen,

$$2O_\ell + C_p (4.35 + \eta_r (1.5\eta_c - 4.0)) = H_d + H_{\ell,n} \qquad (4\text{-}7)$$

The net hydrogen balance for the complete process is,

$$W_v + W_{xs} + W_s + H_e = H_d + C_p(\eta_r(2.0 - 1.5\eta_c)) \qquad (4\text{-}8)$$

Equations 4-7 and 4-8 can be generalized into the following formulations applicable to all four Category 2 methods.

$$2O_\ell + C_pB = H_d + H_{\ell,n} \qquad (4\text{-}9)$$

$$W_v + W_{xs} + W_s = H_d + C_pA \qquad (4\text{-}10)$$

The correlating terms A and B are different for each method; however, they contain only constants and input data values. As these terms do not contain dependent subsystem variables, they may be determined before performing the mass balance computations. The correlating parameters for the four methods are given in Table 4-8. The efficiencies η_r and η_c, applicable to each of the four methods are given in Table 4-9.

Although the previous analysis shows a procedure independent of reduction method for Category 2 systems, four computation procedures illustrated in Figure 4-23, are necessary because of the inclusion of other equipment in conjunction with the reducer to accomplish O_2 recovery. The four electrolysis options that can be used with each of the four O_2 recovery methods are given in Table 4-10. For example, Sabatier with methane vent can be combined with vapor electrolysis and/or water electrolysis.

4.2.3.2 Oxygen Recovery Process Units

In this section and the one which follows, detailed discussions of the recovery and electrolysis units will be given. This will include explanations of the chemical processes, process efficiencies, state of technology development of the process, support hardware and equipment necessary, interaction with other subsystems, and the development of the parametric relations and scaling laws which describe the units and define their operation and capability.

Table 4-8

CATEGORY 2 OXYGEN RECOVERY CORRELATING PARAMETERS

Process	Correlating Parameters A	B
Sabatier	$4.35 - 2.0\ \eta_r$	0
Sabatier - C_2H_2	$\eta_r\ (2.0 - 1.5\ \eta_c)$	$(4.35 + \eta_r\ (1.5\ \eta_c - 4.0))$
Sabatier - C	$\eta_r\ (2.0 - 2.0\ \eta_c)$	$(4.35 + \eta_r\ (2.0\ \eta_c - 4.0))$
Bosch	$\eta_r\ (2.0 - 2.0\ \eta_c)$	$(4.35 + \eta_r\ (2.0\ \eta_c - 4.0))$

Table 4-9

PROCESS EFFICIENCY PARAMETER

Process	η_r	η_c
Sabatier	Data input	Not used
Sabatier - C_2H_2	Data input	Data input
Sabatier - C	Data input	Data input
Bosch	1.0	1.0

Table 4-10

FUNCTIONAL COMBINATIONS FOR O2 RECOVERY BY METHODS IN CATEGORY 2

Option	Electrolysis Vapor	Electrolysis Liquid	O_2	Liquid H_2O
1	Yes	Yes	No	Yes
2	No	Yes	No	Yes
3	No	Yes	Yes	No*
4	No	Yes	Yes	Yes

***As this combination includes a liquid electrolysis unit, electrolysis of any excess water, determined by the Water Management Subsystem water balance, is allowed.**

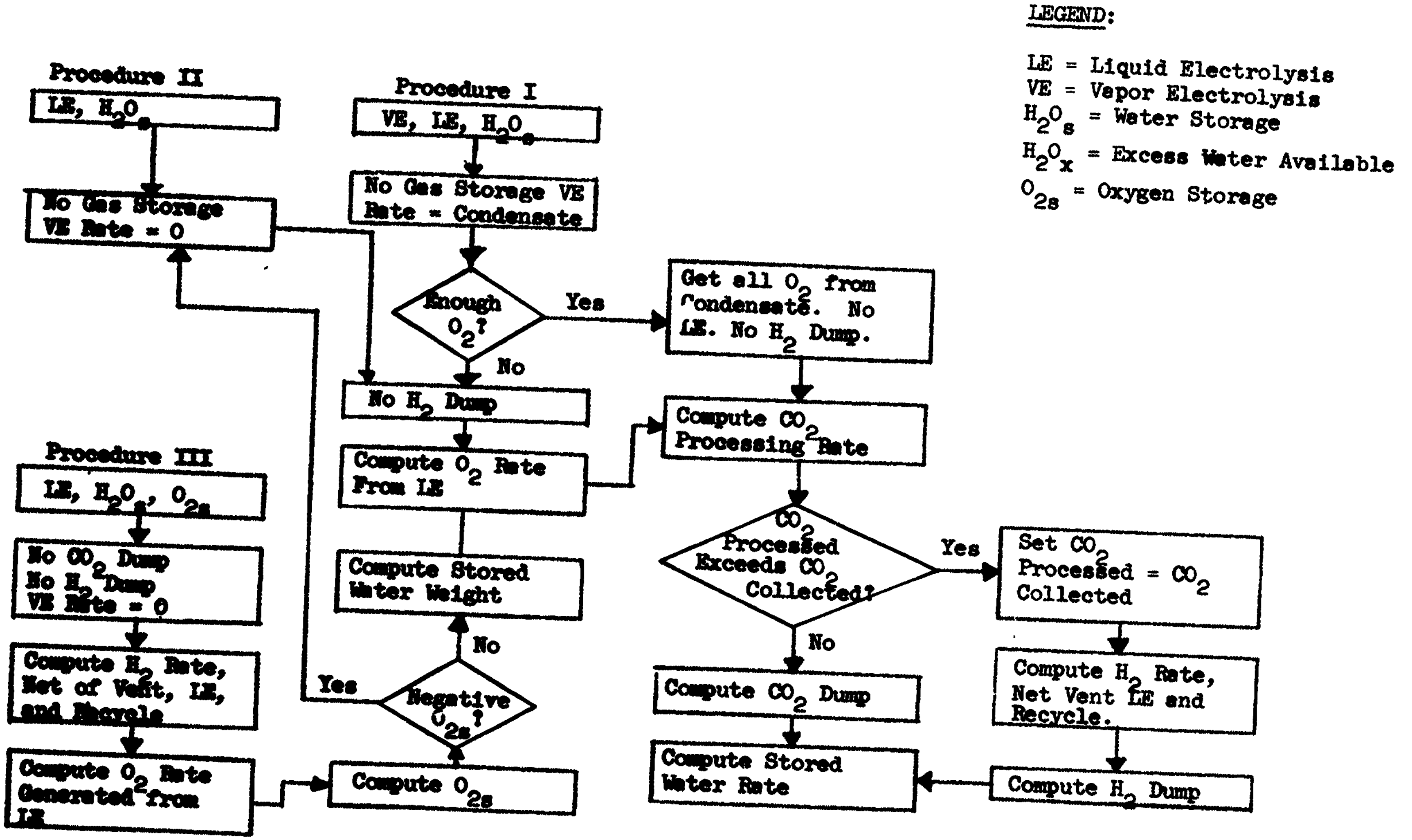


Figure 4-23. Logic Diagram for Oxygen Recovery Mass Balances

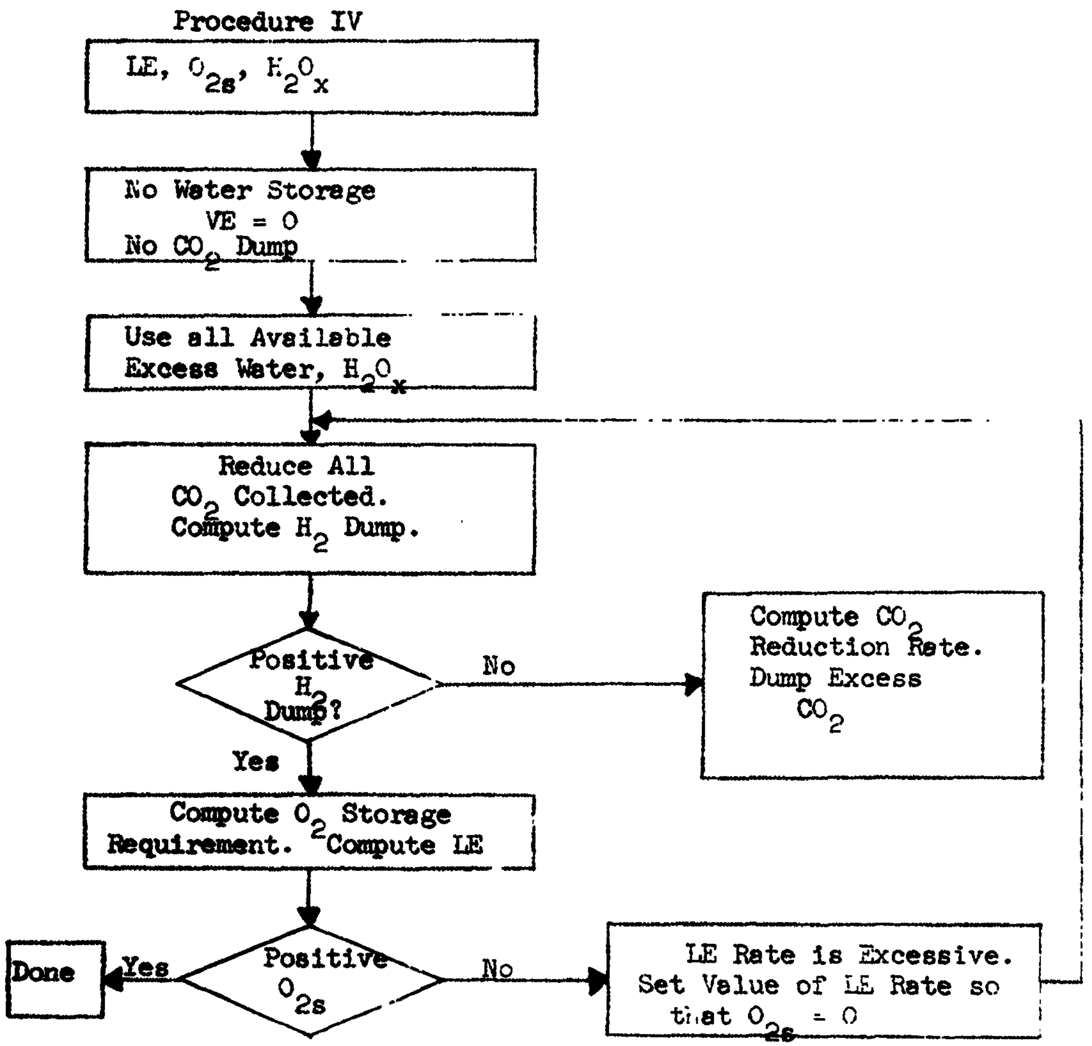


Figure 4-23. (Continued)

Bosch

The Bosch reaction is usually summarized by the following equation:

$$CO_2 + 2H_2 \longrightarrow C + 2H_2O + 595 \text{ watt-hr/kg } CO_2 \qquad (4\text{-}11)$$

The reaction occurs in the presence of an iron catalyst at temperatures of 590° to 980°C (1,100° to 1,800°F). The reaction usually results in a partial conversion, ranging from 30 % at the lower temperatures up to 98 % at the higher temperatures. Bosch reactors are usually operated at temperatures between 590° and 700°C (1,100° and 1,300°F), where maximum formation of carbon occurs. Within this temperature range, it is felt that the reaction takes place in two steps as follows:

$$CO_2 + H_2 \longrightarrow CO + H_2O \qquad (4\text{-}12)$$

and

$$H_2 + CO \longrightarrow C + H_2O \qquad (4\text{-}13)$$

The resulting gases are usually recycled to achieve a higher degree of conversion. The reaction rate is controlled by many apparently independent but nonetheless interrelated variables. The most important variables relate to the conditions in the reactor. These variables may be grouped as the catalyst, the gas stream composition, and the reaction kinetics. Reaction kinetics include the effect of reactor temperature and the gas flow rate or recycle rate through the reaction loop as controlled by the recycle compressor.

Increasing the flow rate through the reactor increases the probable number of collisions per unit time, thereby increasing the reaction rate, and this in turn calls for higher compressor power requirements. Experiments have been conducted to investigate the effects of reactant gas H_2 to CO_2 volume ratio on conversion rates (Reference 4-10). These tests were made with volume ratios ranging from 3 to 9. Conversion rates were found to be somewhat insensitive to the gas ratios; however, a hydrogen-rich ratio was indicated to be better. A volumetric ratio of 4.35 was selected in formulating the design scaling laws for the Bosch CO_2 reducer.

Two types of Bosch units are included here. The first utilizes expendable cartridge catalysts. The other type employs a nonexpendable rotating catalyst. A description of each of the two models used in developing the design scaling laws follows.

Bosch Reducer with Expendable Cartridge Catalyst--A schematic diagram of a Bosch CO_2 Reducer with an expendable cartridge catalyst is shown in Figure 4-24. A compressor is used to circulate carbon dioxide, makeup hydrogen, and recycle gases through the system. The gases are heated in a regenerative heat exchanger by the hot exit gases from the reactor before entering the reactor. Since the process is exothermic, the reactor is basically a canister with startup strap heaters wound around its external circumference. The expendable cartridge is a screen mesh cylinder filled with the steel wool catalyst and placed inside the reactor housing. A steel wool density of approximately 64 kg/m^3 as used in Reference 4-10 experiments is the packing density. A filter is placed downstream of the reactor to trap solid carbon or other particles. The resultant water is condensed in the condenser/H_2O separator, collected, and piped to the Water Supply subsystem.

Design scaling laws for the Bosch CO_2 reducer with expendable cartridge are given in Table 4-11 where (NW_c), the product of number of crew men and their CO_2 production rate, is the processed CO_2 rate in kilograms per day. Table 4-12 shows a detailed component breakdown of a 10-man Bosch CO_2 reducer. Scaled data for the 10-man unit were developed from designs and hardware by TRW, Inc., Batelle Memorial Institute, and General American Transportation Corporation (Reference 4-10 through 4-19).

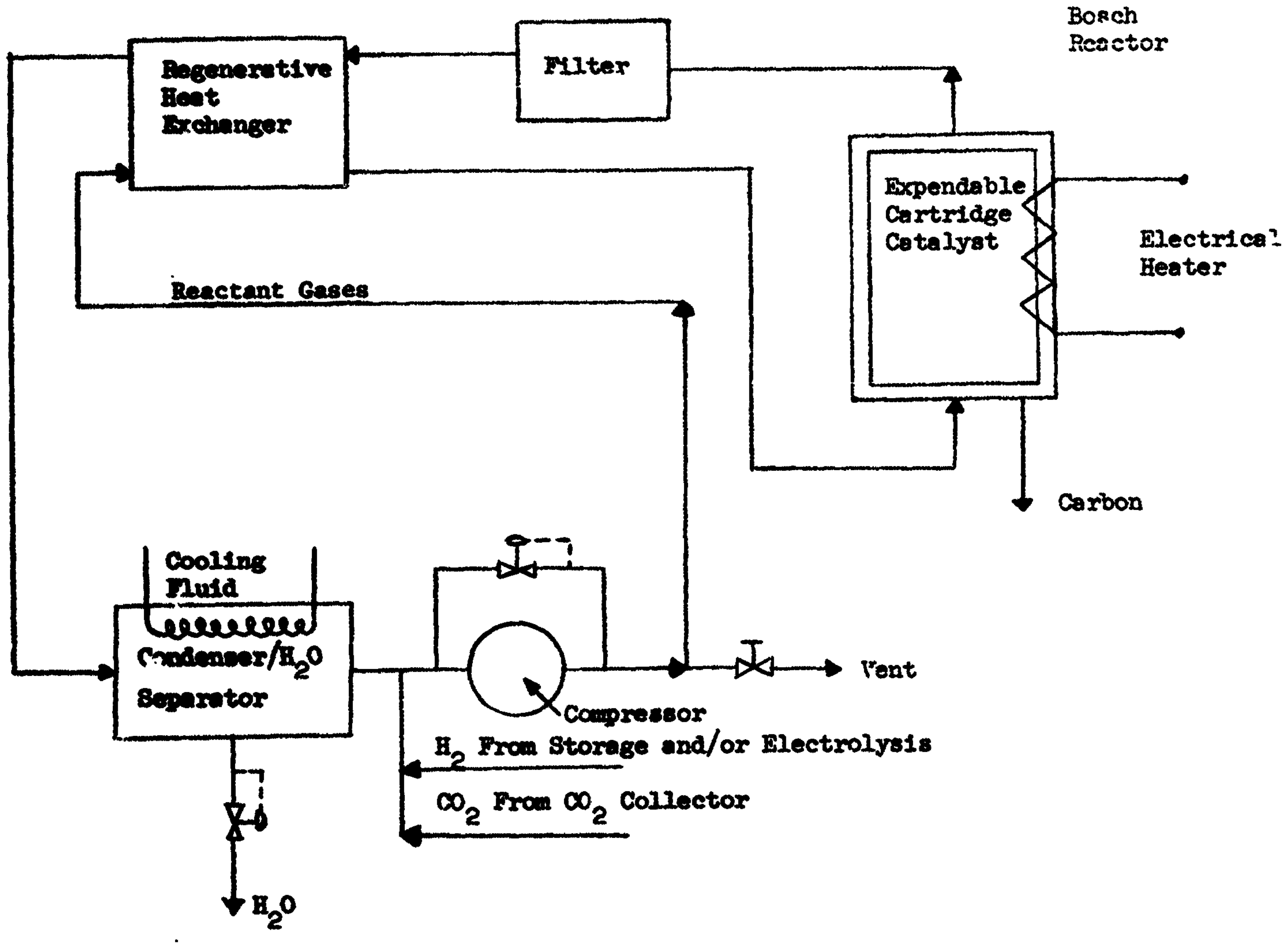


Figure 4-24. Bosch CO_2 Reducer with Expendable Cartridge Catalyst

Bosch Reducer with Rotating Catalyst--This unit (Figure 4-25) is similar to the Bosch reducer with expendable cartridge described above with the exception of the rotating catalyst assembly replacing the catalyst housing and cartridge. The rotating catalyst assembly consists of a hollow center shaft with equally spaced catalyst discs mounted on it. The disks are made of low-carbon steel. The spacing between the disks has been experimentally determined to be at least 0.0635 x 10^{-2} meter for optimum utilization of catalyst surface area (Reference 4-11). In addition, this reference indicates an average reaction gas flow rate of 0.5 cc/min/cm^2 of catalyst surface area. A motor drive, mounted on the reactor, rotates the shaft and catalyst disks. Stationary scrapers that extend from the inner surface of the reactor are used to loosen and remove the solid carbon formed on the catalyst disks. Electrical startup strap heaters are wound around the external housing of the reactor.

Design scaling laws for the Bosch CO_2 reducer with rotating catalyst are given in Table 4-13 where ($N\overline{W}_c$) is the processed CO_2 rate in kilograms per day. Table 4-14 shows a detailed component breakdown of this 10-man Bosch CO_2 reducer. Scaled date for the 10-man Bosch CO_2 reducer. Scaled date for the 10-man unit were based on designs and hardware by TRW, Inc., Batelle Memorial Institute, and General American Transportation Corporation (References 4-10 through 4-20).

Molten Carbonate

The molten carbonate process involves both chemical and electrochemical reactions. When CO_2 is introduced into a molten lithium carbonate electrolysis cell, first, Li_2CO_3 is electrolyzed to Li_2O, carbon, and oxygen. Lithium oxide then reacts with CO_2 to reform lithium carbonate. Carbon, from the first reaction, is deposited on the cathode, while oxygen is generated at the anode to be collected. Experimental work at Hamilton Standard Division of United Aircraft Corporation has indicated that the electrolysis of pure molten carbonate gives satisfactory results (Reference 4-14). Its high melting point of 735°C (1,355°F), thus high operating temperatures, requires

Table 4-11

DESIGN SCALING LAWS FOR BOSCH CO_2 REDUCER WITH EXPENDABLE CARTRIDGE CATALYST

System Weight $= 13.6 + 13.2\,(N\bar{w}_c)^{0.63}$ kg

System Volume $= 0.0522\,(N\bar{w}_c)^{0.51}$ m^3

System Power Requirement $= 10 + 236\,(N\bar{w}_c)^{0.844}$ $watts_e$

Heat Rejection to Atmosphere, Q_{RA} $= 8.75 + 158\,(N\bar{w}_c)^{0.844}$ $watts_t$

Heat Rejection to Coolant, Q_{RC} $= 127\,(N\bar{w}_c)^{0.698}$ $watts_t$

Expendable Weight $= 0.0444\,(N\bar{w}_c)$ kg/day

Expendable Volume $= 0.00112\,(N\bar{w}_c)$ m^3/day

$(N\bar{w}_c)$ = kilograms of CO_2/day

Table 4-12

DETAILS OF A 10-MAN BOSCH CO_2 REDUCER WITH EXPENDABLE CARTRIDGE CATALYST

Component	Fixed Weight kg(lb)	Expendable Weight (kg/day)	Power ($watts_e$)	Q_{RA} ($watts_t$)	Q_{RC} ($watts_t$)
Reactor, cartridge and heater	6.57(14.5)	0.45	780	440	585
Reactor heater power, average			45**		
Insulation, Min-K	22.65(50)				
Heat exchanger	1.59(3.5)				
Compressor	6.80(15)		835	835	
Condenser/H_2O separator	9.97(22)				55
Regulator, valves and tubing	6.80(15)				
Panel and Instrumentation	6.80(15)		10	10	
Structural support	9.06(20)				
TOTAL	70.24(155)	0.45	1,670	1,285	640

---

*Unit total volume = 0.171 m^3 (6 ft^3)

**Based on 720 watts for 3 hours every 2 days

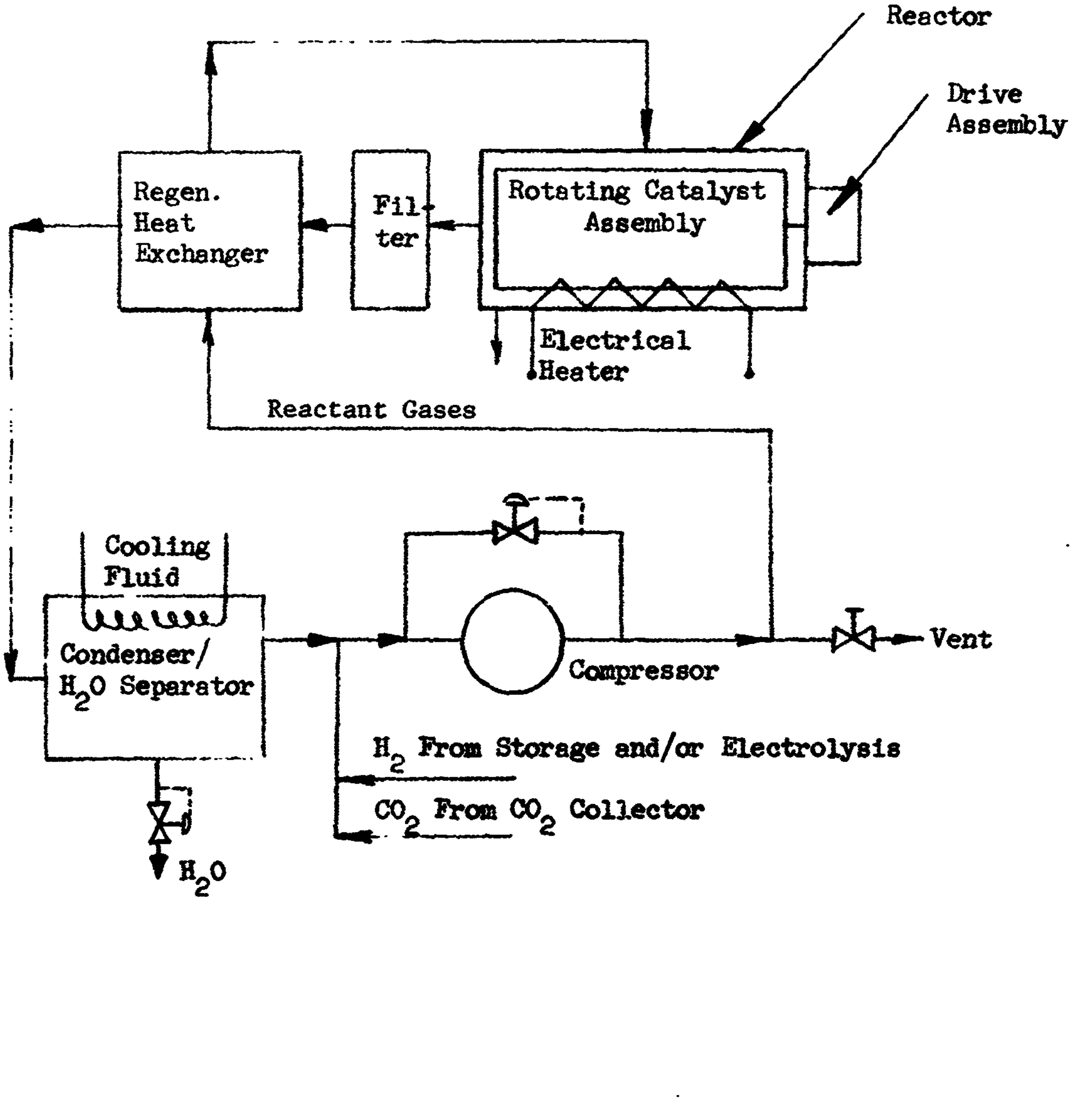


Figure 4-25. Bosch CO_2 Reducer with Rotating Catalyst

Table 4-13

DESIGN SCALING LAWS FOR BOSCH CO_2 REDUCER WITH ROTATING CATALYST

System Weight $= 13.0 + 13.6\ (N\bar{w}_c)^{0.663}$ kg

System Volume $= 0.0216\ (N\bar{w}_c)\ 0.555\ m^3$

System Power Requirement $= 10 + 237\ (N\bar{w}_c)\ 0.84\ \text{watts}_e$

Heat Rejection to Atmosphere, Q_{RA} $= 8\ 79 + 164\ (N\bar{w}_c)\ 0.895\ \text{watts}_t$

Heat Rejection to Coolant, Q_{RC} $= 127.3\ (N\bar{w}_c)^{0.698}\ \text{watts}_t$

Expendable Weight $= 0.01555\ (N\bar{w}_c)$ kg/day

Expendable Volume $= 0.000018\ (N\bar{w}_c)\ m^3/\text{day}$

$(N\bar{w}_c)$ is Kilograms of CO_2/day

Table 4-14

DETAILS OF A 10-MAN BOSCH CO_2 REDUCER WITH ROTATING CATALYST*

Component	Fixed Weight kg (lb)	Power (watts$_e$)	Q_{RA} (watts$_t$)	Q_{RC} (watts$_t$)
Reactor housing and heater	6.57 (14.5)	780	440	505
Heater power		45**		
Rotating catalyst and drive assembly	6.34 (14)	50	50	
Insulation, Min-K	22.65 (50)			
Heat exchanger	1.59 (3.5)			
Compressor	6.80 (15)	835	835	
Condenser/HO_2 separator	9.97 (22)			55
Regulator, valves and tubing	6.80 (15)			
Panel and instrumentation	6.80 (15)	10	10	
Structural support	9.06 (20)			
TOTAL	76.58 (169)	1,720	1,335	640

*Unit Volume = $0.171\ m^3$ ($6.0\ ft^3$)

**Based on 720 watts for 3 hours every 2 days high temperature materials and associated high heat losses. These conditions also accelerate corrosion of the equipment. A lower melting point composition with similar conversion performance was found to be a eutectic mixture containing 60 percent by volume of lithium chloride and 40 percent Li_2CO_3. This eutectic mixture has a melting point of 507°C (943°F).

One of the advantages of the molten carbonate process is that the process reactions do not require the introduction of pure or highly concentrated carbon dioxide but it will accept air directly from the cabin. No concentrator is needed in conjunction with a molten carbonate unit. Another advantage is that the reaction results in the release of oxygen and thus no water electrolysis process is necessary. One of the main design problems of this process concerns the phase separation between the gases and the molten salts, especially in null gravity conditions. Another problem is the removal of carbon deposited on the cathode. The selected molten carbonate unit is based on a design which uses disposable cells that are discarded after a specified quantity of carbon has been deposited on the cathode (Reference 4-14). A porous matrix, made of sintered magnesium oxide, is used as cathode. When wetted by the melt, a stable interface is formed in the matrix because of capillary surface tensions. The matrix should be dense enough to hold the electrolyte in place under all gravity conditions, yet sufficiently porous to allow ion mobility and an efficient process. A screen (the anode) surrounds the electrolyte and the matrix. The anode screen and cathode matrix are held together by a metal diaphragm which deflects to accomodate the carbon deposited in the matrix. A number of cells, each containing the anode, cathode and metal diaphragm forms a stack. The unit is so designed that stacks can be replaced with fresh units whenever they are filled with carbon.

A schematic diagram of the molten carbonate CO_2 reduction unit is shown in Figure 4-26. A blower is used to deliver cabin air to the anode cavity. A regenerative heat exchanger is used to heat the incoming air and conserve some of the process heat. An electrical heater is used to maintain the carbonate and the process. A heat control unit senses the melt temperature

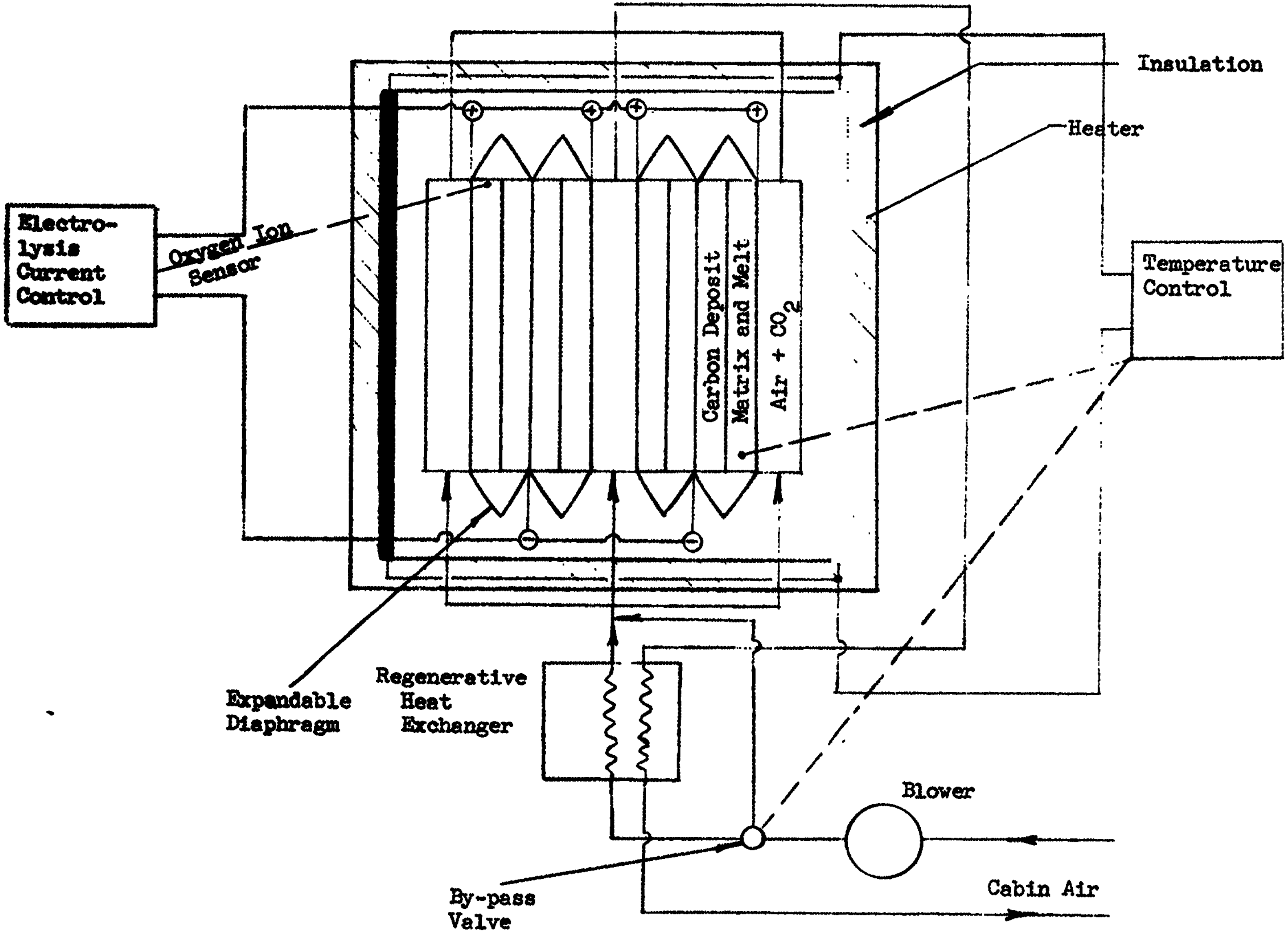


Figure 4-26. Molten Carbonate CO_2 Reducer

and regulates a control valve to bypass a portion of the incoming air around the heat exchanger thus providing the required amount of cooling to keep the carbonate within the operating temperature range. A current controller is required to regulate the cell current. This controller uses an oxygen ion sensor located in the cell to monitor the oxide ion concentration, which is a function of the rate of CO_2 decomposition.

Design scaling laws for the molten carbonate CO_2 reducer are given in Table 4-15, where $(N\bar{w}_c)$ is the processed CO_2 rate in kilogram per day. Table 4-16 shows a detailed breakdown for a 10-man molten carbonate CO_2 reducer. Scaled data for the 10-man unit were based on designs and developed hardware by Hamilton Standard Division (References 4-20 through 4-25). The unit design was based on the following assumptions:

1. Cell current density = 320 amps/m^2
2. Zero-current cell voltage = 1.46 volts
3. Inlet air temperature = 21.1° ± 8.2°C (70° ± 15°F)
4. 70% CO_2 removal effectiveness per pass through the system.
5. 100% oxygen recovery from CO_2.
6. CO_2 concentration in cabin atmosphere = 3.8 mm Hg

Solid Electrolyte

The solid electrolyte unit involves both a chemical and electrochemical process. The solid electrolyte operates at approximately 1,100°C (2,000°F), and it is basically a ceramic tube made of several chemicals. A mixture of 8.75 mole percent Y_2O_3 and 91.25 mole percent Z_rO_2 was found to provide good structural and electrical characteristics for the tube (Reference 4-26). Electrodes are applied to the inner and outer surfaces of the tube walls and the tubes are heated internally by an auxiliary heating coil. The concentrated CO_2 is introduced to the outside of the tube, and the O_2 is liberated from inside the tube. It is felt that in the chemical process the oxygen comes from a thermal decomposition of CO_2 and CO to oxygen at the cathode surface and where the oxygen atom is ionized. This oxygen ion then migrates under the influence of a potential field through vacancies in the crystal lattice of the solid electrolyte material to the anode, and where the oxygen ion is converted to an oxygen atom. The power consumption in the cell is split

Table 4-15

DESIGN SCALING LAWS FOR MOLTEN CARBONATE CO_2 REDUCER

System Weight* = $27.6 + 29.1\ (N\bar{w}_c)^{0.57}$ kg

System Volume = $0.087\ (N\bar{w}_c)^{0.465}\ m^3$

System Power Requirements = $1{,}580\ (N\bar{w}_c)^{0.695}$ watts_e

Expendable Weight = $0.251\ (N\bar{w}_c)$ kg/day

Expendable Volume = $0.00106\ (N\bar{w}_c)\ m^3$/day

Heat Rejection to Atmosphere, Q_{RA} = $1030\ (N\bar{w}_c)^{0.7}$ watts_t

$N\bar{w}_c$ is in Kilograms of CO_2/day

---

*The system weight does not include the cell stacks which are treated as expendables.

Table 4-16

DETAILS OF A 10-MAN MOLTEN CARBONATE CO_2 REDUCER*

Component	Fixed Weight Kg(lb)	Expendable Weight kg/day	Power (watts_e)	Q_{RA} (watts_t)
Cell stacks, including $LiCO_3$ and LiCl		2.55	4,500	1,800
Regenerative heat exchanger	25.39 (56)			
Blower	6.80 (15)		450	450
Heater	9.06 (20)		3,000	3,000
Insulation	22.65 (50)			
Container	18.12 (40)			
Structural Support, instrumentation, etc.	49.83 (110)		10	10
TOTAL	131.89 (291)	2.55	7,960	5,260

---

*Total unit volume = $0.257 m^3$ ($9.0\ ft^3$)

between energy required to decompose the CO_2 and the resistance heating of the solid electrolyte material. As the predicted cell efficiency is thought to be good and the operating temperature high, this unit must be well insulated to prevent heat leakage which would decrease unit performance. The auxiliary heater in the cell tube is designed to bring the tube to operating temperature.

The free energy change involved in the decomposition of CO_2 to carbon monoxide and to oxygen is 123 kcal/gram-mole of oxygen. This corresponds to a theoretical power requirement for a cell of 136 watts/kg of CO_2 per day.

The mixture of CO and CO_2 from the cell cathode is passed through a catalytic reactor which converts CO to CO_2 (returned to the electrolytic cell) and to solid carbon. The free energy change in this reaction is 29 kcal/gram-mole of carbon. This corresponds to a heat dissipation requirement of 735 watts/kg of CO_2 per day.

A flow diagram of a solid electrolyte system is given in Figure 4-27 which shows that after leaving the electrolytic cell, the gases are mixed with those emerging from the regenerative heat exchanger. The operating temperature of the catalytic reactor is about 510°C (950°F). In the catalytic reactor, the carbon monoxide is combined to form carbon and carbon dioxide over a nickel catalyst. When the resultant carbon has built up to a high level, a pressure switch will sense the increasing differential pressure and signal for a change of catalyst bed. The catalytic reaction is exothermic and no heating of this unit is necessary once the system has reached operating temperature. The gases which leave the catalytic reactor give up some of their heat in the regenerative heat exchanger. A compressor circulates the gases through the system as shown in the schematic.

One of the main advantages of the solid electrolyte unit is that it produces oxygen without the need of a water electrolysis unit. Design scaling laws for the solid electrolyte CO_2 reducer with expendable cartridges are given in Table 4-17, where $(N\tilde{w}_c)$ is the processed CO_2 rate in kilograms per day.

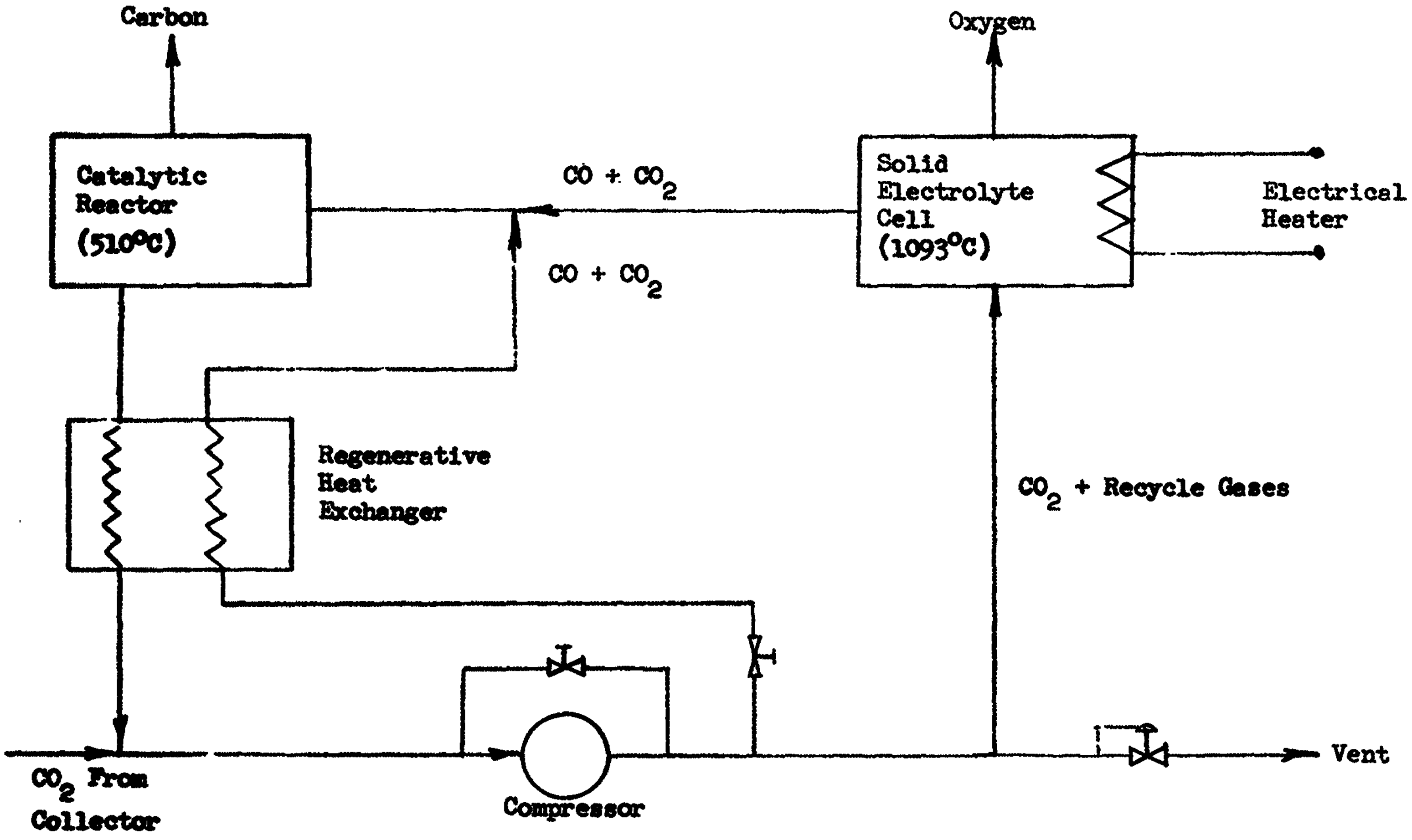


Figure 4-27. Solid Electrolyte CO_2 Reducer

Table 4-18 shows a detailed component breakdown of a 10-man solid electrolyte CO_2 reducer. Scaled data for the 10-man unit were based on designs and experimental hardware by the Isomet Corporation and Lockheed Missiles and Space Company (References 4-23 through 4-26).

Sabatier

The Sabatier process involves the hydrogenation of CO_2 over a 204° to 371°C (400° to 700° F) catalyst in a reactor. This may be followed by subsequent reactions, such as for the recovery of hydrogen from methane. The Sabatier reaction is summarized by the following equation:

$$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O \qquad (4\text{-}14)$$

The Sabatier water product is electrolyzed to oxygen, for breathing, and to hydrogen for return to the Sabatier reactor. The Sabatier stoichiometric ratio of 1 to 4 for complete conversion of CO_2 to methane is not optimum in an actual unit. Optimum reaction rates have been experimentally determined to be a molar ratio of 1:4.35. This ratio has been used in this report. Extremely short reactor beds may introduce channeling and extremely long beds result in a high pressure drop, but space velocity appears to have a much greater influence on the reaction rate than mass velocity. Space velocity is volume dependent and is characterized by the volume of feed in a unit time per volume of catalyst. The reaction products, CH_4 and H_2O, were found to have little effect on the Sabatier reaction rate.

Formulation of the design scaling laws for the Sabatier CO_2 reduction system is based on experience with a 4-man unit built by the Garrett Corporation and man-tested in the MDAC-WD Space Cabin Simulator during a 60-day test program (Reference 4-27). The Sabatier reaction is exothermic. It requires a startup heater, but should operate continuously. The reaction involves only a single pass through the Sabatier reactor, with conversion efficiencies ranging up to over 99% (Reference 4-28). If a Sabatier reaction efficiency, η_s, is taken into account, Equation 4-14 may be rewritten as:

$$CO_2 + 4H_2 \rightarrow \eta_s CH_4 + \eta_s H_2O + (1 - \eta_s) CO_2 + (1 - \eta_s) H_2 \qquad (4\text{-}15)$$

Table 4-17

DESIGN SCALING LAWS FOR SOLID ELECTROLYTE CO_2 REDUCER

System Weight = $22.6 + 23.9\,(N\bar{w}_c)^{0.66}$ Kg.

System Volume = $0.035 + 0.042\,(N\bar{w}_c)^{0.66}$ Ft^3

System Power Requirement = $895\,(N\bar{w}_c)^{0.745}$ $watts_e$

Heat Rejection to Atmosphere, Q_{RA} = $657\,(N\bar{w}_c)^{0.785}$ $watts_t$

Expendable Weight = $0.0444\,(N\bar{w}_c)$ Kg. /Day

Expendable Volume = $0.00097\,(N\bar{w}_c)$ m^3/Day

$(N\bar{w}_c)$ is in Kilograms of CO_2/Day

Table 4-18

DETAILS OF A 10-MAN SOLID ELECTROLYTE UNIT*

Component	Weight Kg(lb)	Expendable Weight kg/day	Power ($watts_e$)	Q_{RA} ($watts_t$)
Electrolytic cell	22.65 (50)		3950	2600
Insulation	15.86 (35)			
Catalytic reactor	31.71 (70)	0.45		360
Compressor	11.33 (25)		1,100	1,100
Regenerative heat exchanger	2.72 (6)			
Instrumentation and controls	22.65 (50)			
Structural support, valves, plumbing, Etc.	24.92 (55)			
TOTAL	131.84 (291)	0.45	5,050	4,060

---

*Total Unit Volume = 0.235 m^3 (8.31 ft^3)

Equations 4-14 and 4-15 show that approximately half of the hydrogen may be lost to the system if it is not recovered from CH_4. Two processes are suggested for this purpose: one, the acetylene former, and the other, the methane cracker. A description of these two processes, as well as the basic Sabatier system, are given in the following paragraphs.

Sabatier Reduction Unit With Methane Vent--This is the basic Sabatier reaction process as indicated by Equations 4-14 and 4-15. A schematic of the Sabatier unit with CH_4 vent is shown in Figure 4-28. CO_2 from the CO_2 reservoir and hydrogen from storage and/or electrolysis units are admitted to the Sabatier reactor. The condenser and water separator are used to collect the water vapor before the output gases are vented to space. The condensed water is routed to the water electrolysis unit where it is decomposed to metabolic oxygen and hydrogen. Makeup hydrogen needed for the Sabatier reaction may be supplied either by electrolyzing the output water, the atmospheric condensate, and water carried for this purpose, or by stored hydrogen. All of these methods are considered and are discussed in the section on oxygen recovery mass balances.

Design scaling laws for the Sabatier CO_2 reducer with methane vent are given in Table 4-19 where ($N\bar{w}_c$) is the process CO_2 rate in kilogram per day. Table 4-20 shows a detailed component breakdown of a 10-man Sabatier CO_2 reducer. Scaled data for the 10-man unit were based on prototype hardware, designs and test data (References 4-27 through 4-37).

Sabatier Reduction Unit with Acetylene Vent--This process utilizes the same basic Sabatier CO_2 reduction unit assembly described above but added to it is an acetylene former and a hydrogen stripper as shown in Figure 4-29. Methane from the basic Sabatier unit is converted in the acetylene former to C_2H_2 and hydrogen as shown by the following equation:

$$2CH_4 \longrightarrow C_2H_2 + 3H_2 \qquad (4\text{-}16)$$

The mixture then passes through the hydrogen stripper which is basically a thin-walled sintered palladium alloy tubes permeable only to hydrogen. The

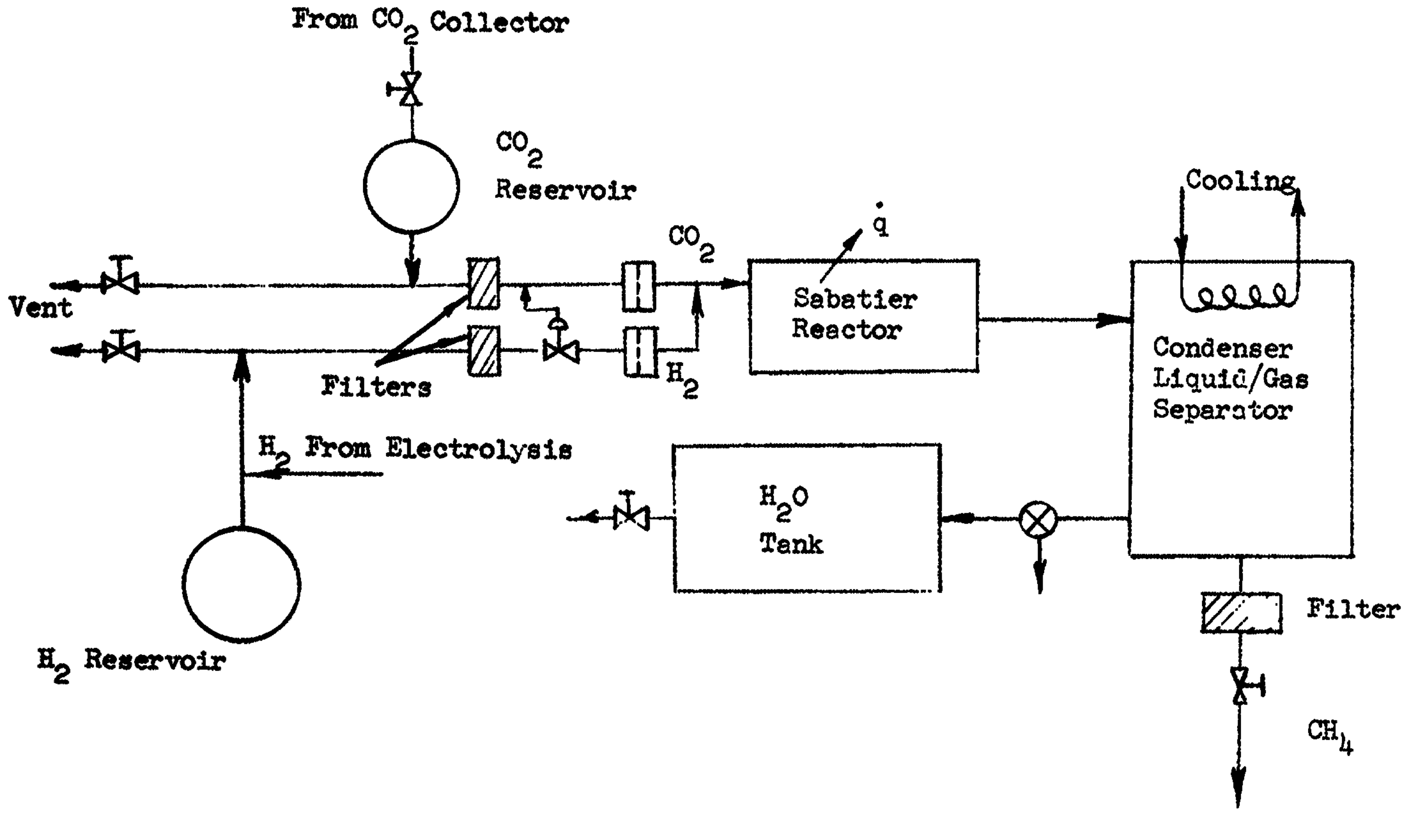


Figure 4-28. Sabatier CO_2 Reducer with Methane Vent

Table 4-19

DESIGN SCALING LAWS FOR SABATIER CO_2 REDUCER WITH METHANE VENT

System Weight $= 14.5 + 8.7\ (N\bar{w}_c)^{0.57}$ kg

System Volume $= 0.04595\ (Nw_c)^{0.39}\ m^3$

System Power Requirement $= 25 + 1.64\ (N\bar{w}_c)$ watts_e

Heat Rejection to Atmosphere, Q_{RA} $= 25 + 37.8\ (N\bar{w}_c)^{0.699}$ watts_t

Heat Rejection to Coolant, Q_{RC} $= 19.9\ (N\bar{w}_c)$ watts_t

(Nw_c) - Kilograms of CO_2/Day

Table 4-20

DETAILS OF A 10-MAN SABATIER CO_2 REDUCER WITH METHANE VENT*

Component	Fixed Weight kg (lb)	Power (watts_e)	Q_{RA} (watts_t)	Q_{RA} (watts_t)
Reactor	4.53 (10)		175	
Insulation	13.59 (30)			
Condenser and water separator	5.44 (12)			195
Valves, controls and instrumentation	14.50 (32)	41.7	41.7	
Structural support and plumbing	9.06 (20)			
TOTAL	47.12 (104)	41.7	216.7	195

***Unit Total Volume = 0.114 m^3 (4 ft^3)**

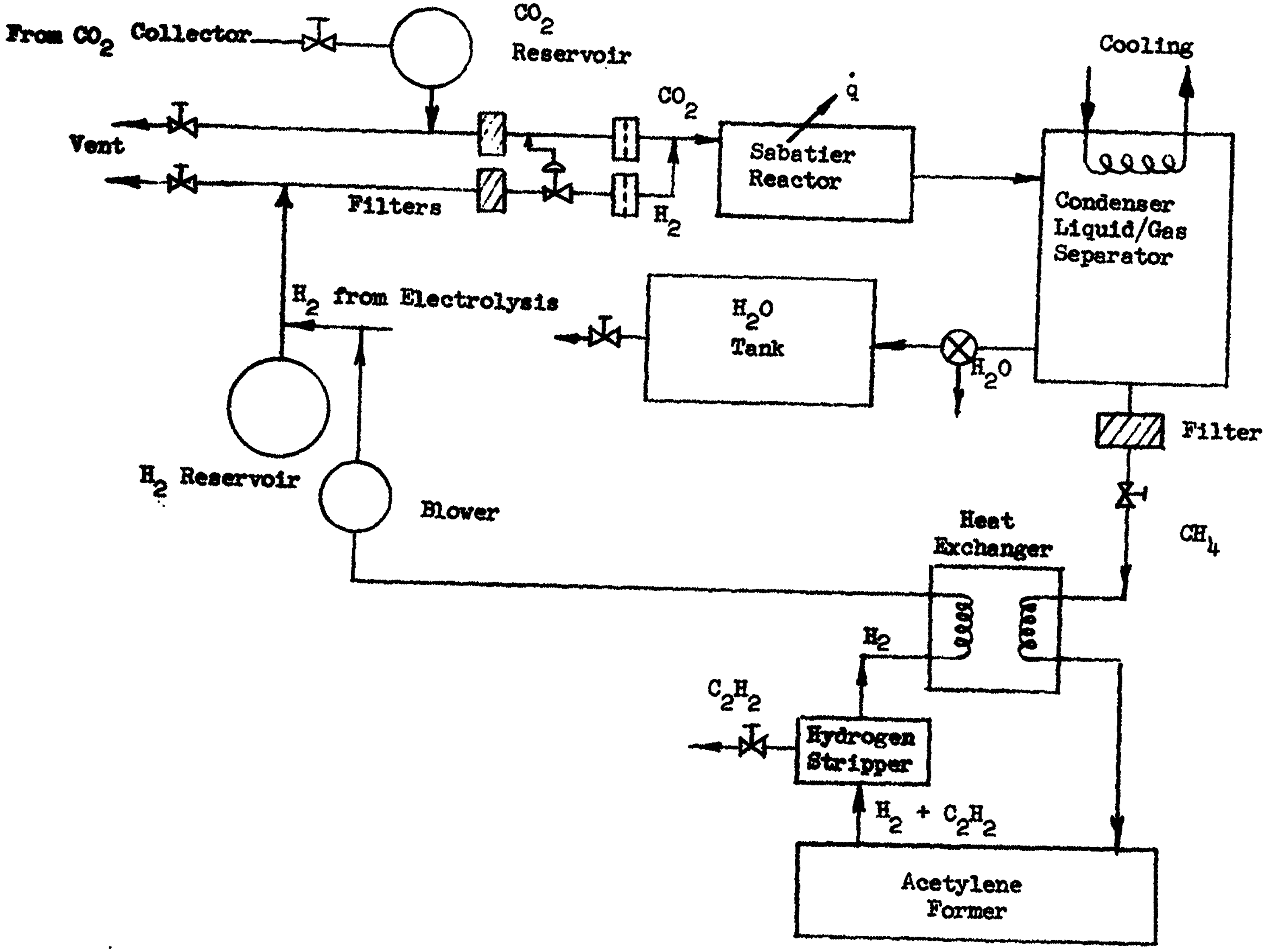


Figure 4-29. Sabatier CO_2 Reducer with Acetylene Vent

hydrogen is collected in the [illegible] around the tube. The heavier C_2H_2 molecules continue through the stripper where they may be vented or disposed of.

Design scaling laws for the Sabatier CO_2 reducer with acetylene vent are given in Table 4-21, where $(N\bar{w}_c)$ is the processed CO_2 rate in kilograms per day. Table 4-22 shows a detailed component breakdown of a 10-man Sabatier CO_2 reducer with acetylene vent. Scaled data for the 10-man unit were based on designs, hardware, and test data (References 4-29 through 4-37).

Sabatier Reduction Unit with Methane Cracker--This process uses the basic Sabatier reduction unit with the addition of a cracker. A schematic of this process is shown in Figure 4-30. The dry methane is routed to a high-temperature (982°C) methane cracker where it is decomposed to carbon and hydrogen according to the following equation:

$$CH_4 \longrightarrow C + 2H_2 \qquad (4\text{-}17)$$

Design scaling laws for the Sabatier CO_2 reducer with methane cracker are given in Table 4-23, where (Nw_c) is the rate of CO_2 processed in kilograms per day. Table 4-24 shows a detailed breakdown of a 10-man Sabatier unit with methane cracker. Scaled data for the 10-man unit were based on concepts, designs, hardware, and test data (References 4-29 through 4-37).

Table 4-21

DESIGN SCALING LAWS FOR SABATIER CO_2 REDUCER WITH ACETYLENE VENT

System Weight = $14.5 + 10.5\ (N\bar{w}_c)^{0.781}$ kg
System Volume = $0.0436\ (N\bar{w}_c)^{0.636}\ m^3$
System Power Requirement = $25 + 22.95\ (N\bar{w}_c)$ $watts_e$
Heat Rejection to Atmosphere, $Q'_{RA} = 25 + 83.1\ (N\bar{w}_c)^{0.915}$ $watts_t$
Heat Rejection to Coolant, $Q_{RC} = 19.22\ (N\bar{w}_c)$ $watts_t$
Nw_c - kilograms of CO_2/day

TABLE 4-22
DETAILS OF A 10-MAN SABATIER CO_2 REDUCER WITH ACETYLENE VENT*

Component	Fixed Weight kg (lb)	Power (watts_e)	Q_{RA} (watts_t)	Q_{RA} (watts_t)
Reactor	4.53 (10)		175	
Insulation	13.59 (30)			
Condenser and H_2O separator	5.44 (12)			195
Valves, controls, and instrumentation	14.50 (32)	41.7	41.7	
Structural support and plumbing	9.06 (20)			
Acetylene former and supports	20.39 (45)	400	400	
H_2 stripper and supports	11.33 (25)	100	100	
TOTAL	78.84 (174)	541.7	716.7	195

*Unit total volume = 0.19 m^3 (6.7 ft^3)

4.2.3.3 Electrolysis Units

Figure 4-21 shows the major electrolysis units that appear to have the best potential for being used in a space operational unit. These electrolysis units use either water or water vapor. The selected units considered in this study were the following:

1. Rotating cell with hydrogen diffusion
2. Double membrane cell with H_2SO_4 electrolyte
3. Water vapor cell
4. Membrane cell with KOH electrolyte

Rotating Cell with Hydrogen Diffusion

In the rotating electrolysis unit with hydrogen diffusion, the centrifugal forces produced by the cell rotation are used to establish a hydrostatic pressure gradient in the electrolyte, so that the evolved gases will flow toward

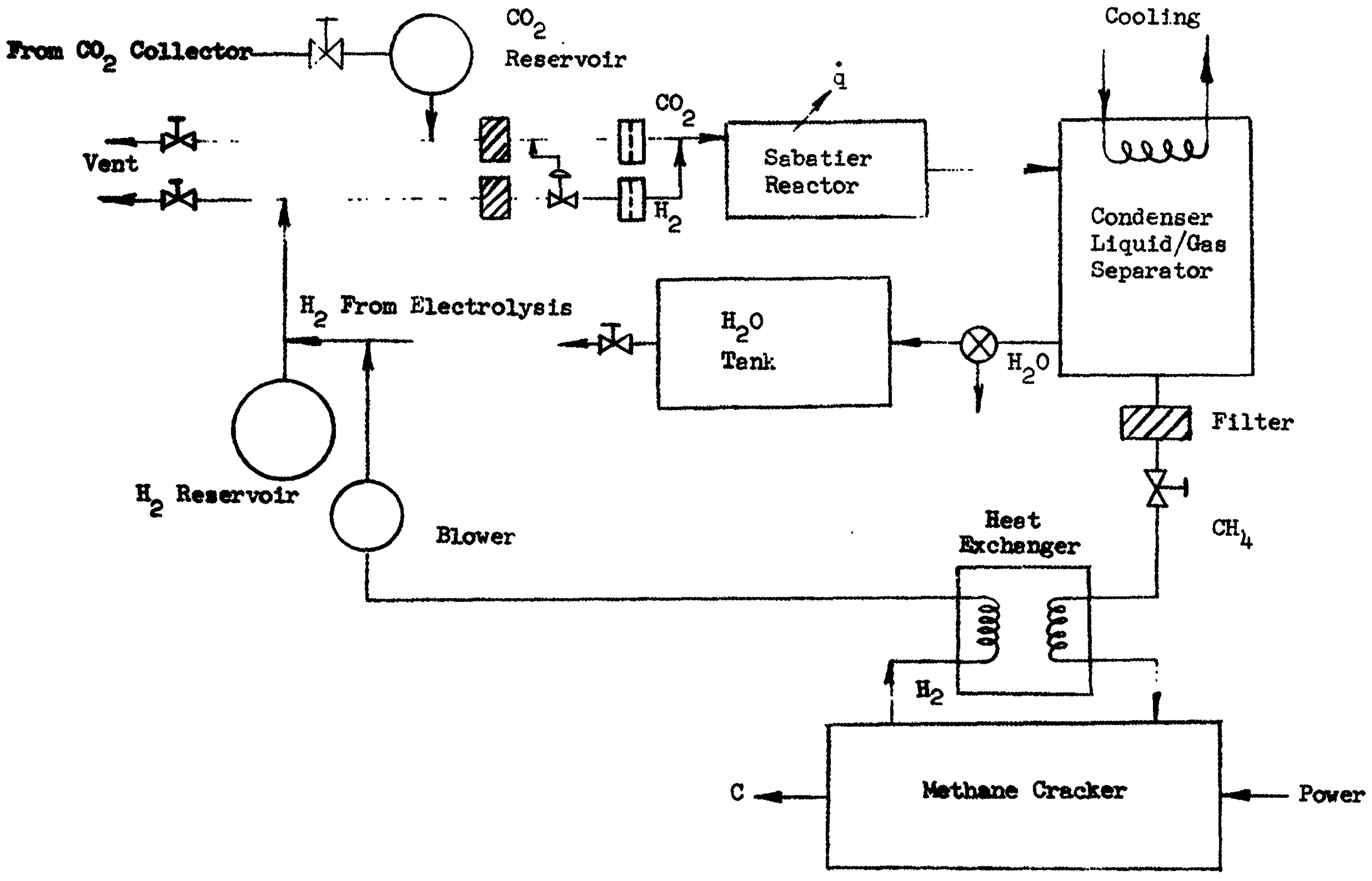


Figure 4-30. Sabatier CO_2 Reducer with Methane Cracker

Table 4-23

DESIGN SCALING LAWS FOR SABATIER CO_2 REDUCER WITH METHANE CRACKER

System Weight = $14.5 + 11.6\ (N\bar{w}_c)^{0.819}$ kg

System Volume = $0.03466\ (N\bar{w}_c)^{0.685}\ m^3$

System Power Requirement = $25 + 80\ (N\bar{w}_c)$ watts_e

Heat rejection to atmosphere, Q_{RA} = $25 + 111\ (N\bar{w}_c)^{0.943}$ watts_t

Heat rejection to coolant, Q_{RC} = $19.22\ (N\bar{w}_c)$ watts_t

Nw_c - Kilogram of CO_2/day

Table 4-24

DETAILS OF A 10-MAN SABATIER CO_2 REDUCER WITH METHANE CRACKER*

Component	Fixed Weight, kg (lb)	Power (watts_e)	Q_{RA} (watts_t)	Q_{RA} (watts_t)
Reactor	4.53 (10)		175	
Insulation	13.59 (30)			
Condenser and H_2O separator	5.44 (12)			195
Valves, controls, and instrumentation	14.50 (32)	41.7	41.7	
Structural supports and plumbing	9.06 (20)			
Methane cracker, carbon collector, and supports	45.30 (100)	800	800	
TOTAL	92.42 (204)	841.7	1,016.7	195

---

*Unit Total Volume = $0.23\ m^3$ ($8.16\ ft^3$)

the center of rotation and separate from the electrolyte. This unit is of interest for zero gravity applications. Separation of the evolved gaseous hydrogen and oxygen is accomplished by a palladium foil hydrogen diffusion cathode that will permit the flow of hydrogen in a gaseous phase to the side of the cathode opposite the side with the hydrogen-oxygen mixture. As the cathode operation is by diffusion, it is independent of gravity. Reference 4-38 indicates that tests of this type have shown successful cathode operation at current densities up to 1,290 amps/m^2. It also predicts that cathode current densities up to 3,490 amps/m^2 at 2.0 volts might be attainable in the future at temperatures below 230°C and with 100% hydrogen transmission.

The design scaling laws which have been formulated here are based on a model with the following characteristics:

Current Density = 1,079 amps/m^2
Cell Voltage = 2.0 volts
Number of Cells = 14 per module

The number of modules per cell and the cell area, and consequently the current, are the variables which may be changed to accommodate the oxygen or hydrogen load requirement. Design scaling laws for the rotating cell with hydrogen diffusion are given in Table 4-25, where $(N\bar{w}_o)$ is the rate of oxygen to be supplied by the unit in kilograms per day, and M is umber of modules per unit. The design scaling laws are based on hardw designs, and experimental results performed by the Batelle Memorial Institute (References 4-38 through 4-40).

Double Membrane Cell with H_2SO_4 Electrolyte

In the double membrane cell, water with about 32% by weight of H_2SO_4 added to make it conducting, is fed into the narrow space between two ion-exchange membranes. Each membrane assembly has a thin screen catalyst/electrode bonded to the outer face, where the gaseous electrolysis products are evolved. The screen is of platinum with a platinum black coating. The membranes are current conductors and provide a liquid-gas separation.

Table 4-25

DESIGN SCALING LAWS FOR ROTATING CELL WITH H_2 DIFFUSION ELECTROLYSIS UNIT

Cell Area, $A_c = 9.8 \times 10^{-3} (N\bar{w}_o)/M$ m^2

Cell Current, $I_c = 1080 A_c$ amps

System Weight $= 1.36 + 0.6 (N\bar{w}_o) + 1.15 (N\bar{w}_o)^{0.5} + 276 M A_c$ kg

System Volume $= 2.9 M A_c$ m^3

System Power Requirement $= (15 + 28 I_c) M + 20$ watts

Heat Rejection to Atmosphere, $Q_{RA} = (15.2 + 10.8 I_c) M + 20$ watts

Expendable Weight $= 0.01 (N\bar{w}_o)$ kg/day

Expendable Volume $= 7.48 \times 10^{-6} (N\bar{w}_o)$ m^3/day

---

This process is independent of gravity. The three-phase contact of liquid electrolyte with gaseous products across the ion-exchange membrane is reportedly quite stable; however, considerable pressure difference must be sustained without displacing this electrolyte contact. Test results indicate that the cells may operate at a 0.351 kg/cm^2 (5 psi) differential for long periods, and the pressure difference for short-term operation may be as much as 2.81 kg/cm^2 (40 psi) without malfunction.

The double membrane electrolysis cell with H_2SO_4 electrolyte used as a model for developing these design scaling laws is based on hardware and designs by the General Electric Company (References 4-41). Data were modified and scaled to fit the following assumptions:

Current density = 432 amps/m^2
Cell voltage = 2.05 volts
Number of cells = 14 cells/module
Operation duty cycle = 95% of the time

The number of modules per unit and the cell area were allowed to vary with the H_2 and O_2 demand requirements. Design scaling laws for the unit are presented in Table 4-26, where ($N\bar{w}_o$) is the rate of oxygen to be supplied by the unit in kilograms/day and M is the number of modules/unit.

Water Vapor Cell

The water vapor electrolysis unit processes water vapor perspired and respired into the cabin atmosphere by crewmen. LiOH generates water vapor during CO_2 absorption but combining this functional method and the water vapor cell is not used in conjunction with O_2 recovery for this study. The maximum water vapor removal rate permitted by the water vapor electrolysis cell is that which balances the net water vapor generation rate minus the loss due to cabin leakage. This electrolysis unit obtains its water directly from the moisture in the cabin atmosphere. A wicking material holds the electrolyte, which is phosphoric acid in this application, between the anode and cathode. The unit is made of a number of cells, each consisting of the anode and cathode screens and a

Table 4-26

DESIGN SCALING LAWS FOR THE DOUBLE MEMBRANE CELL WITH H_2SO_4 ELECTROLYTE

Cell are, $A_c = 2.44 \times 10^{-2} \, (N\bar{w}_o)/M \ m^2$

Cell current, $I_c = 432 \, A_c$ amps

System weight $= 1.36 + 0.6 \, (N\bar{w}_o) + 1.15 \, (N\bar{w}_o)^{0.5} + 199 \, MA_c$ kg

System volume $= 0.254 \times 10^{-2} + 0.35 \, MA_c + 0.0157 \, (N\bar{w}_o)^{0.775} \ m^3$

System power requirements $= (15 + 28.7 \, I_c) \, M + 20$ watts

Heat rejection to atmosphere, $Q_{RA} = (1.5 + 1.15 \, I_c) M + 1.98$ watts

Heat rejection to coolant, $Q_{RC} = (13.5 + 10.3 \, I_c) \, M + 17.9$ watts

Expendable weight $= 0.015 \, (N\bar{w}_o)$ kg/day

Expendable volume $= 1.13 \times 10^{-5} \, (N\bar{w}_o) \ m^3$/day

---

pad of microporous rubber acting as the wicking material. Electrolysis dehydrates the electrolyte and delivers hydrogen at the cathode and oxygen at the anode. New moisture then rehydrates the electrolyte and the process is continued.

Water vapor removal is normally accomplished by the dehumidifying condenser in the atmosphere purification loop. Use of the water vapor electrolysis cell thus supplements or, in the extreme case, may supersede this condenser during normal operating conditions. If the vapor electrolysis cell is limited by the maximum allowable water vapor removal rate (and cabin makeup O_2 has not been achieved), the liquid water electrolysis unit may be employed to supply the O_2 deficit.

The vapor cell electrolysis cell with H_2SO_4 electrolyte used as a model for developing design scaling laws here is based on hardware and designs by Batelle Memorial Institute (References 4-42 through 4-44). Data were modified and scaled to fit the following assumptions:

Current density = 216 amps/m^2
Cell voltage = 2.34 volts

Design scaling laws for the unit are presented in Table 4-27, where:

$(N\bar{w}_o)$ = rate of oxygen processed, kg/day
μ = viscosity of atmospheric gas, kg/m sec
v = specific volume of gas, m^3/kg
h_1 = inlet gas humidity ratio, kg H_2O/kg dry air
h_2 = outlet gas humidity ratio, kg H_2O/kg dry air
C_p = specific heat of gas, watt-hours/kg °C

Membrane Cell with KOH Electrolyte

This electrolysis unit is typical of units built or under development at Allis-Chalmers Company and TRW, Inc. (Reference 4-45 through 4-48). They are cells having screen electrodes and between which the KOH electrolyte is held within a fibrous matrix. Makeup water is continuously carried from

Table 4-27

DESIGN SCALING LAWS FOR WATER VAPOR ELECTROLYSIS CELL

System Weight $= 6.8 + 5.4\ (\bar{w}_o N) + 1.39\ (\bar{w}_o N)^{0.5}$ kg

System Volume $= 0.705 \times 10^{-2} + 0.0083\ (\bar{w}_o N)^{0.9}\ m^3$

System Power requirement $= 5 + (11{,}300\ \mu q^2) + 329\ (N\bar{w}_o)$ watts

Expendable Weight $= 0.015\ (\bar{w}_o N)$ kg/day

Expendable Volume $= 1.13 \times 10^{-5}\ (\bar{w}_o N)\ m^3$

Heat Rejection to atmosphere, $Q_{RA} = 5 + (11{,}300\ \mu q^2) + (153\ \bar{w}_o N)$ watts

Pressure drop in cell $= 6{,}800 \frac{\mu v}{h_1}\ kg/m^2$

Required gas flow $q = \frac{1.56 \times 10^{-3} \times v \times (w_o N)}{h_1 - h_2}\ m^3/min$

Temperature rise in gas stream, $\Delta T = \frac{0.045 \times 10^{-3}\ \bar{w}_o N}{\frac{60q}{v} \times C_p}\ ^\circ C$

---

the water transport matrix to the electrolyte matrix where it is electrolyzed to H_2 and O_2. In addition to the cells, the electrolysis unit includes a current controller, back-pressure regulators for each of the two gas lines, a water supply regulator, and control instrumentation.

Data for the model used in formulating the design scaling laws, for the membrane cell with KOH electrolyte unit, were modified and scaled from References 4-47 and 4-48 to fit the following assumptions:

Current density = 1,180 amps/m^2
Cell voltage = 1.65 volts
Number of cells = 17 cells/module

The number of modules per unit and the cell area were allowed to vary with the hydrogen and oxygen demand requirements. Design scaling laws for the unit are presented in Table 4-28, where $(N\bar{w}_o)$ is the rate of oxygen to be supplied by the unit in kilograms/day and M is the number of modules/unit.

Table 4-28

DESIGN SCALING LAWS FOR THE MEMBRANE CELL WITH KOH ELECTROLYTE

Cell area, $A_c = 7.7 \times 10^{-3} (N\bar{w}_o)/M \ m^2$

Cell current, $I_c = 1180 \ A_c$ amps

System weight $= 1.36 + 0.5 (Nw_o) + 1.15 (Nw_o)^{0.5} + 726 \ MA_c$ kg

System volume $= 0.254 \times 10^{-2} + 13.4 \ MA_c \ m^3$

System power requirements $= (15 + 28 \ I_c) M + 20$ watts

Heat rejection to atmosphere, $Q_{RA} = (12.7 + 5.95 \ I_c) M + 17$ watts

Heat rejection to coolant, $Q_{RC} = (2.24 + 1.05 \ I_c) M + 2.93$ watts

---

4.2.4 Airlock

The airlock is a compartment with separate hatches opening either to the space vehicle cabin or to space, which permits the entry or exit from the vehicle for extravehicular activities without loss of all the cabin atmosphere.

Recent studies (Reference 4-7) have shown a weight advantage by the addition of an airlock pump to the airlock when the airlock is used for five or more times on a mission. The airlock pump saves most of the airlock atmosphere by pumping it into the adjacent cabin and the weight of atmosphere so saved is greater than the weight of the sum of the pump and the equivalent weight of the required pump power.

It was found that closed-form analytical equations could be formulated for determinations of cabin atmosphere lost through airlock usage and associated airlock pump power and weight. The assumptions, equations, and procedure used for determining airlock characteristics follow.

4.2.4.1 Assumptions

The following assumptions were used to determine airlock characteristics:

- Airlock and cabin atmospheres behave as ideal gases
- Airlock expansion during pumpdown is adiabatic (low pressures and low gravity reduce heat transfer)
- Cabin compression is isothermal since the cabin thermal control system removes heat of compression
- The airlock atmosphere is pumped into a sealed cabin until the final airlock pressure is reached. The remaining airlock atmosphere is then dumped overboard.
- The pumpdown procedure requires 15 min
- The initial cabin and airlock temperatures and pressures are identical.
- The volumetric discharge from the pump is constant.
- Power scheduling efficiency of 50% (this efficiency is discussed later).

4.2.4.2 Procedure

Airlock specifications required are:

P_i	initial pressure, kg/cm^2
P_{af}	final airlock pressure, kg/cm^2
V_a	airlock volume, m^3
V_c	cabin volume, m^3
T_i	initial temperature, °K
ϵ	pump efficiency

A combination of the ideal gas law and the adiabatic expansion relationship is solved for the amount of airlock atmosphere expended per use. This amount, m_{af}, is

$$m_{af} = \frac{(MW)\, P_i\, V_a}{R\, T_i} \left(\frac{P_{af}}{P_i}\right)^{1/\gamma} \left(\frac{10^4\ \text{cm}^2}{\text{m}^3}\right),\ \text{kg} \qquad (4\text{-}18)$$

This is converted to an equivalent use rate,

$$\dot{m}_{af} = \frac{m_{af} \times N_{al}}{\theta}, \frac{kg}{hr} \qquad (4\text{-}19)$$

where,

MW = atmosphere molecular weight, kg/kg-mole

R = universal gas constant, $846 \frac{kg\ m}{kg\text{-mole}\ °K}$

N_{al} = total number of airlock uses per resupply period or mission

θ = resupply period or mission duration, hr

γ = ratio of specific heats

For subsystems without a pump, P_{af} equals P_i and the above equation gives the initial amount of airlock atmosphere.

The equation of state combined with the above result is used to compute the amount of atmosphere in the sealed cabin at the conclusion of pumpdown. This amount, m_{cf}, is the sum of initial cabin atmosphere and the recovered airlock atmosphere

$$m_{cf} = \frac{(MW)\ (V_c + V_a)}{R\ T_i} - m_{af},\ kg \qquad (4\text{-}20)$$

The theoretical pump energy, E, is calculated by subtracting the adiabatic work of expansion of the residual airlock atmosphere, m_{af}, from the isothermal work of compression of the atmosphere compressed in the cabin, m_{cf}.

The resultant energy is:

$$E = \frac{R\ T_i}{(MW)} \left(m_{cf} \ln \frac{P_{cf}}{P_i} + \frac{\gamma}{\gamma - 1}\ m_{af} \left[\left(\frac{P_{af}}{P_i} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right] \right) kW\text{-}hr \qquad (4\text{-}21)$$

where R is the ideal gas constant in energy units, $3.23 \times 10^{-3} \frac{\text{kW-hr}}{\text{kg-mole °K}}$

The 15-min pumpdown period and pump efficiency E, determine the average power requirement, P_{ave}, as

$$P_{ave} = \frac{60 \text{ min/hr}}{15 \text{ min}} \frac{E}{\epsilon}, \text{ kW} \tag{4-22}$$

Since pumpdown is assumed to take only 15 min and airlock usage rates are about once per day, it can be assumed that other equipment will be off during the pumpdown.

Equivalent continuous power can therefore be used in lieu of average power in assessing requirements for this functional item. A power scheduling efficiency can be used to determine the percentage of time during which this equivalent power is assumed to be operative. As noted above this efficiency is assumed to be 50%.

Equivalent continuous power is determined through use of a power scheduling factor, f_{ps},

$$f_{ps} = \frac{(15 \text{ min/airlock use})\ (N_{al})}{(\theta \text{ hr})\ \frac{60 \text{ min}}{\text{hr}}\ (\text{Power scheduling efficiency} = 50\%)}$$

$$= \frac{N_{al}}{2\theta} \tag{4-23}$$

The final equivalent power, is then

$$\overline{P} = \frac{P_{ave}\, N_{al}}{2\theta}, \text{ kW} \tag{4-24}$$

A weight scaling law for the airlock pump (Reference 4-6) uses the pump volumetric flow as the independent variable. With the assumption of constant volumetric flow, the flow in terms of volume divided by density may be integrated from initial to final density.

When the adiabatic relationships are used to replace the densities with pressure the volumetric flow, Q, obtained is:

$$Q = \frac{60}{15} \frac{V_a}{\gamma} \ln \frac{P_i}{P_{af}}, \frac{m^3}{hr} \tag{4-25}$$

This result is then used to size the airlock pump, and the scaling law for the airlock pump is:

$$W_p = 2.3 + 0.1\,Q, \text{ kg} \tag{4-26}$$

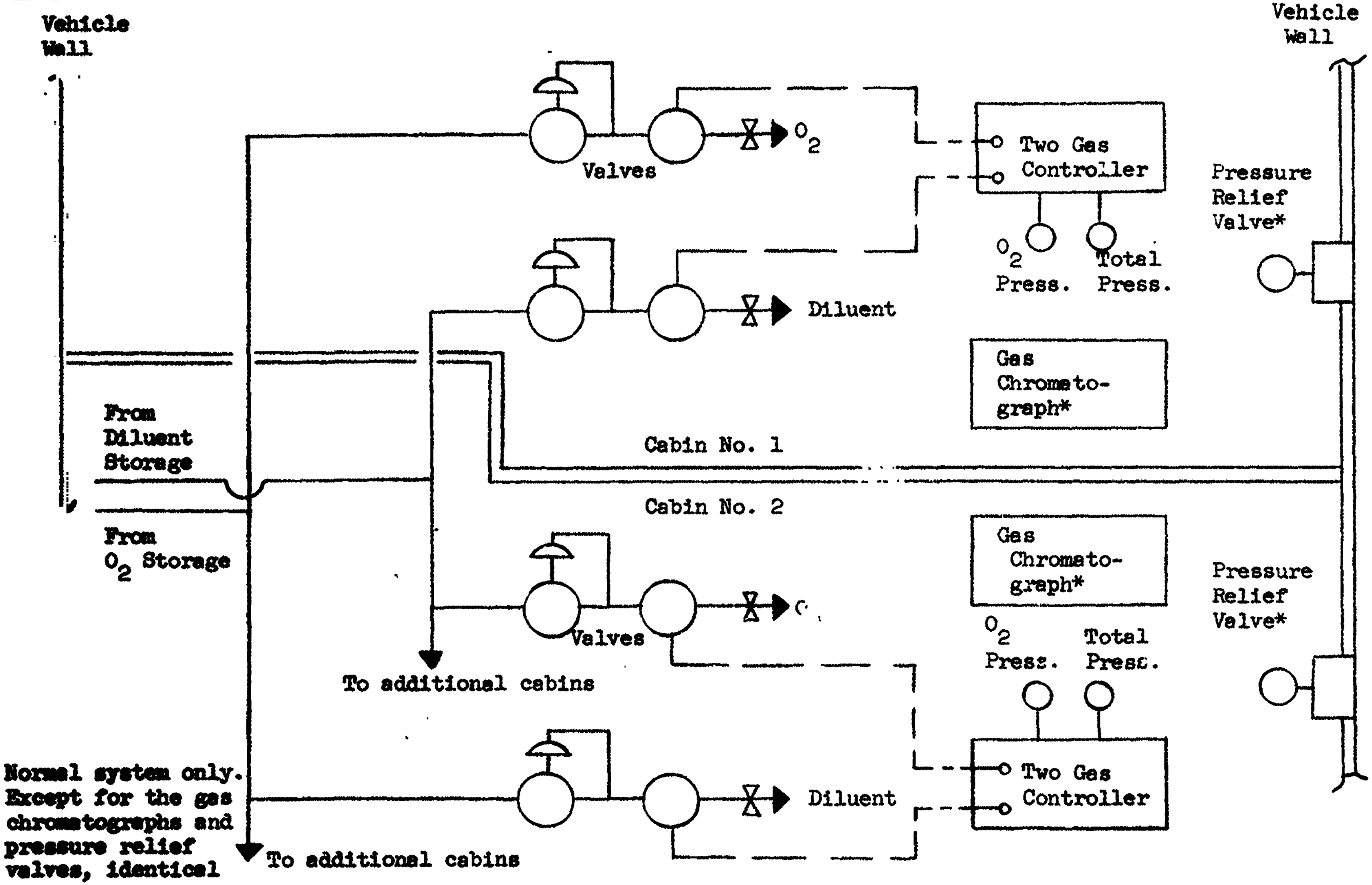
4.2.5 Multiple Cabin Considerations

The concept of considering multiple cabins has significant bearing on gas storage and especially the O_2 recovery. The specified O_2 recovery method, when used, is assumed to be used in each occupied cabin. This assumption is included in the assumptions concerning balances for gaseous constituents discussed in Subsection 4.2.1. This assumption is that mass balances for gaseous constituents are determined for each cabin, and that equipment associated with control of these constituents, with the exception of the actual gas storage vessels, are similarly determined for each cabin.

Gas makeup requirements are determined for each cabin and these summed to determine the total gas makeup rates. Gas storage requirements for O_2 and diluent gas are then determined for specified numbers of tanks and/or tank shapes for the complete life support system. As an optional consideration each cabin may have specified an associated adjacent airlock with individually specified number of airlock uses, airlock volume, and pump performance criteria.

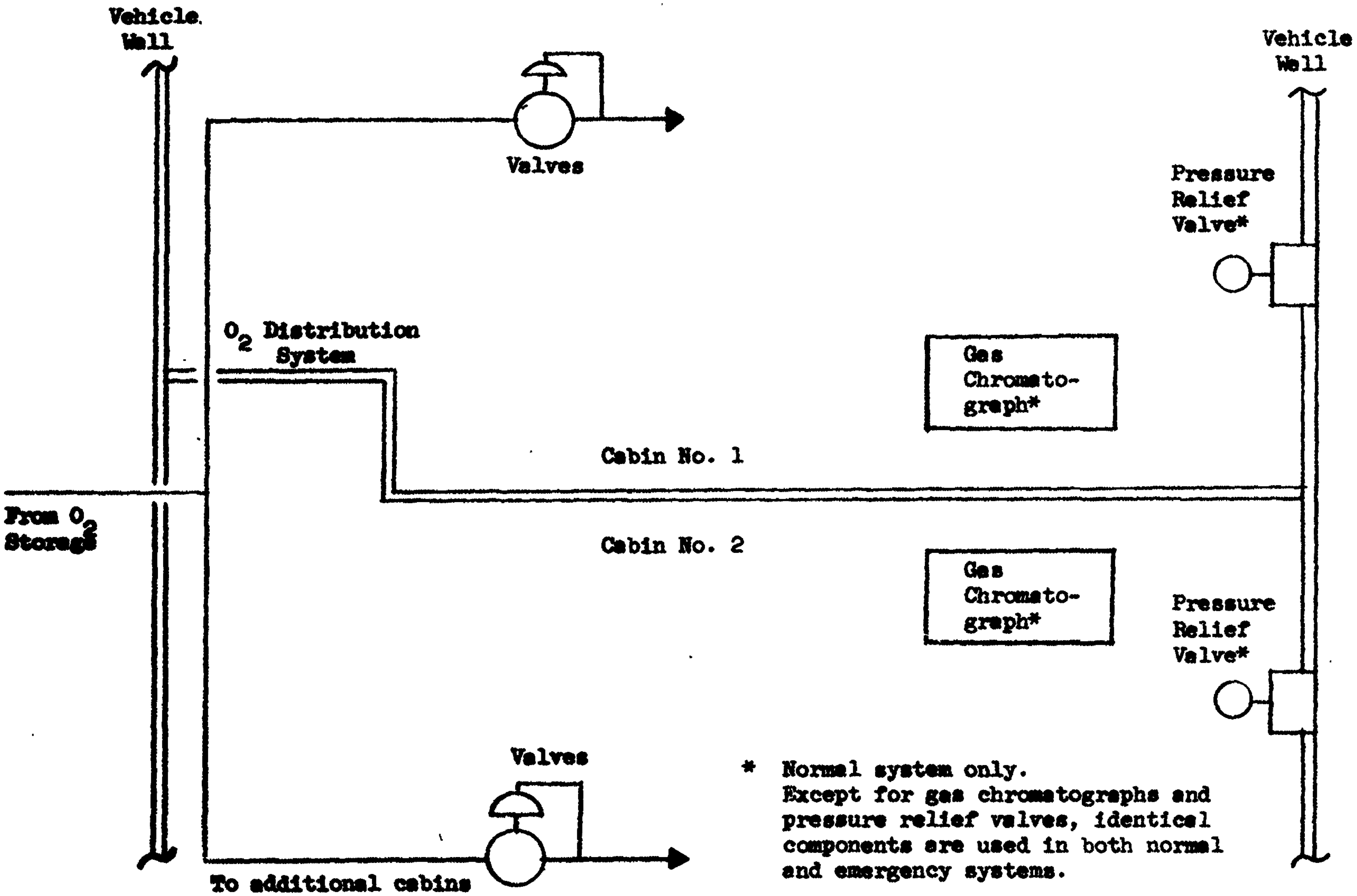
4.2.6 Cabin Pressure Control and Gas Distribution System

The distribution systems and cabin pressure controls for a cabin two gas or single gas supply systems are indicated on Figures 4-31 and 4-32. It has



* Normal system only. Except for the gas chromatographs and pressure relief valves, identical components are used in both normal and emergency systems.

Figure 4-31. Atmospheric Constituent Distribution System and Cabin Pressure Controls for Normal and Emergency Two-Gas Supply Systems



* Normal system only.
Except for gas chromatographs and pressure relief valves, identical components are used in both normal and emergency systems.

Figure 4-32. Single-Gas (O_2) Distribution System and Cabin Pressure Controls for Normal and Emergency Supply Systems been assumed for this study that the aluminum alloy distribution tubing is 1.27×10^{-2} m in diameter and 0.071×10^{-2} m wall. The diameter used is estimated as an average for the range of vehicle sizes considered. Larger vehicles generally necessitate longer distribution systems, and therefore larger tubing diameters might be used to maintain reasonable gas pressure drops.

The total length of tubing for distribution systems is estimated by assuming a length equal to the vehicle length serving as a header with individual lengths connected to this header supplying flow to each cabin. The lengths of these tubes for each cabin are assumed to be equal to the specified vehicle diameter. The basic weight of the tubing is increased by 20% to account for fittings and attachment devices. Thus, the weight of the distribution system, W_{DS}, in terms of input data can be written as follows:

$$W_{DS} = 1.2\left(\sum_{i=1}^{N\leq 6} \frac{4\,V_c\,(i)}{\pi D_v^2} + N\,D_v\right)\left(0.0405\ \frac{kg}{m}\right) \qquad (4\text{-}27)$$

where,

$V_c\,(i)$ = Volume of ith cabin, m^3

D_v = Vehicle diameter, m

N = Number of cabins

Weights and power requirements for the cabin pressure controls for two-gas atmosphere systems were scaled from the latest unclassified Manned Orbital Laboratory (MOL) data (Reference 4-6). Control equipment included in the reference system are provided for normal cabin supply, emergency/repressurization supply, regulated oxygen supply, and cabin pressure relief. The individual components consist of solenoid valves, pressure regulator valves, two gas controller, total pressure transducer, and pressure relief and dump valves.

In addition to the components included in the reference system, it is assumed that a flight-type gas chromatograph is included for control. This device is used for monitoring constituent levels for O_2, diluent CO_2, water

vapor, and some trace contaminants. It can be used for periodic recalibrations of the O_2 partial pressure transducers as well as for overall gas monitoring. For missions longer than 60 days, it is assumed that the O_2 partial pressure transducer is replaced by a flight-type mass spectrometer. This device provides continuous readings for O_2, diluent, CO_2, and water vapor pressures.

Weight and power requirements for gas controls are shown in Table 4-29. Two-gas supply refers to atmospheres consisting of O_2 and with either N_2 or He as the diluent.

4.3 THERMAL CONTROL SUBSYSTEM

The thermal control subsystem includes those components which provide adequate circulation of atmosphere for crew comfort, control atmospheric humidity and temperature, provide heat removal and heat addition interchanges with other functional components, and provide adequate cabin wall thermal insulation. During normal operation, cabin atmosphere and equipment cooling are fundamentally accomplished by transferring heat through heat transfer devices to a liquid coolant and subsequently rejecting the heat to space by a space radiator. Evaporation of expendable water may be required to supplement the process for short periods of time when the external thermal environment limits space radiator capabilities. During emergency periods involving failure of the liquid cooling system, cooling is provided by means of a water evaporator. Coolant interchange is provided between the evaporator and functional components requiring liquid cooling during these emergency periods.

The following functional groups of components comprise the thermal control subsystem and they will be discussed in the order listed:

1. Vehicle Wall Insulation
2. Atmosphere Cooling Equipment
    A. Cabin heat exchangers and associated fans
    B. Dehumidifying condenser, water separator, blower (for normal operation), compressor (for emergency operation), and controls. The ducting and valves connecting these and other components in the gas purification loop are also included in the thermal control subsystem.
    C. Cabin atmosphere circulation fan.

Table 4-29

GASEOUS STORAGE CONTROLS (Page 1 of 2)

Application	Components	Weight (kg)	Power (watts)
Short mission two-gas cabin supply	Valves (regulating, solenoid, relief, and manual)	11.0	
	Two-gas controller	3.3	4.0
	O_2 pressure transducer	0.7	0.5
	Total pressure transducer	0.9	0.6
	Gas chromatograph	5.4	10.0
	Structure	2.3	
	TOTAL	23.6	15.1
Long mission two-gas cabin supply	Valves (regulating, solenoid, relief, and manual)	11.0	
	Two-gas controller	3.3	4.0
	Mass spectrometer	3.7	3.7
	Total pressure transducer	0.9	0.6
	Gas chromatograph	5.4	10.0
	Structure	2.3	
	TOTAL	26.6	18.3
O_2 cabin supply (no diluent)	Valves (regulating, manual and relief)	7.3	
	Gas chromatograph	5.4	10.0
	TOTAL	12.7	10.0

Table 4-29 (Page 2 of 2)

Application	Components	Weight (kg)	Power (watts)
Emergency/repressurization two-gas cabin supply	Valves (regulating, solenoid, and manual)	5.3	
	Two-gas controller	3.3	4.0
	O_2 pressure transducer	0.7	0.5
	Total pressure transducer	0.9	0.6
	Structure	2.3	
	TOTAL	12.5	5.1
Emergency/repressurization O_2 cabin supply (no diluent)	Valves (regulating and manual	1.6	
Emergency atmosphere purifiction loop O_2 supply (closed-loop mode)	Valves (regulating, check manual, and relief)	2.9	

3. **Liquid Cooling and Heating Loops**
   A. **Liquid cooling loop, space radiator loop, interface heat exchanger (thermally joining cooling and radiator loops), water evaporator assembly, and controls. Fluid, tubing, and pumps are included in this group of components.**
   B. **Emergency water evaporator, steam vent, water supply and controls.**
   C. **Liquid heating loop including interface heat exchanger, fluid, tubing, pump and controls.**
4. **Miscellaneous Equipment**

4.3.1 Vehicle Wall Insulation

Vehicle wall insulation is needed to prevent excessively cold or hot inner surfaces of cabin walls and to avoid the requirement for large cabin heating rates or large cabin cooling rates. If inner surface temperatures fall below the cabin atmospheric dew point temperature. moisture condensation will occur on the walls. This may lead to impairment of crew and equipment performance. On the other hand, a too heavily insulated wall results in high insulation weights and prevents a significant amount of passive thermal control from occurring by heat transfer out of the cabin wall.

The best compromise of the above characteristics appears to be obtained by having sufficient insulation so that the minimum inner surface wall temperature will always be a safe temperature increment above the cabin dew point temperature. This increment is set at 2.8°C (5°F) for this study. For example, with a cabin atmosphere at 70°F the inner surface temperatures should be at least 46°F and 63°F for relative humidities of 35% and 65%, respectively. The corresponding spacecraft external wall condition is that provided by no incident heat flux and the vehicle is locally exposed to deep space. This condition of the spacecraft outer wall seeing only deep space is the basis for determining the insulation requirements.

The insulation characteristics are used in the subsequent determination for other environmental conditions of nominal wall heat transfer rates, either into or out of the vehicle. These heat transfer rates are used in sizing the cabin thermal control subsystem. The insulation characteristics also are used in the determination of meteoroid and radiation shielding requirements.

All missions considered for this study can have flight conditions where a portion of the vehicle wall is exposed to an effective sink temperature of near absolute zero for an appreciable time. As this condition is the most severe in terms of condensation on the wall inner surface, it is used in determining the insulation required. In the computations, the inside wall film heat transfer coefficient is assumed to be 5.7×10^{-4} kW/m^2 °K (0.1 Btu/hr ft^2 °F). This is an estimated average value for the type of cabin atmospheres and the relative gas velocities in the vicinity of cabin walls considered for this study.

An expression for required insulation characteristics can be developed by writing the heat transfer equations from the cabin interior to space. See Figure 4-33 for the cabin wall model. Heat transfer across the inner shell boundary layer is

$$\frac{q}{A} = h\,(T_c - T_w) \qquad (4\text{-}28)$$

Heat transferred across the wall is

$$\frac{q}{A} = \frac{K}{L}\,(T_w - T_o) \qquad (4\text{-}29)$$

and the net heat lost to space from the outer shell is

$$\frac{q}{A} = \sigma \epsilon_t T_o^{\,4} \qquad (4\text{-}30)$$

where

$\frac{q}{A}$ = heat transferred (kW/m^2)

h - inside wall film coefficient ($kW/m^2\ °K$)

T_c - cabin atmosphere temperature (°K)

T_w - inside wall temperature (°K)

K - insulation thermal conductivity ($kW/m^2\ °K$)

L - insulation thickness (meters)

T_o - outside wall temperature (°K)

σ - Stefan - Boltzmann constant ($kW/m^2\ °K^4$)

ϵ_t - emmissivity of cabin outer wall for thermal radiation

Equation 4-30 is based on the outer wall radiating directly to space at absolute zero temperature.

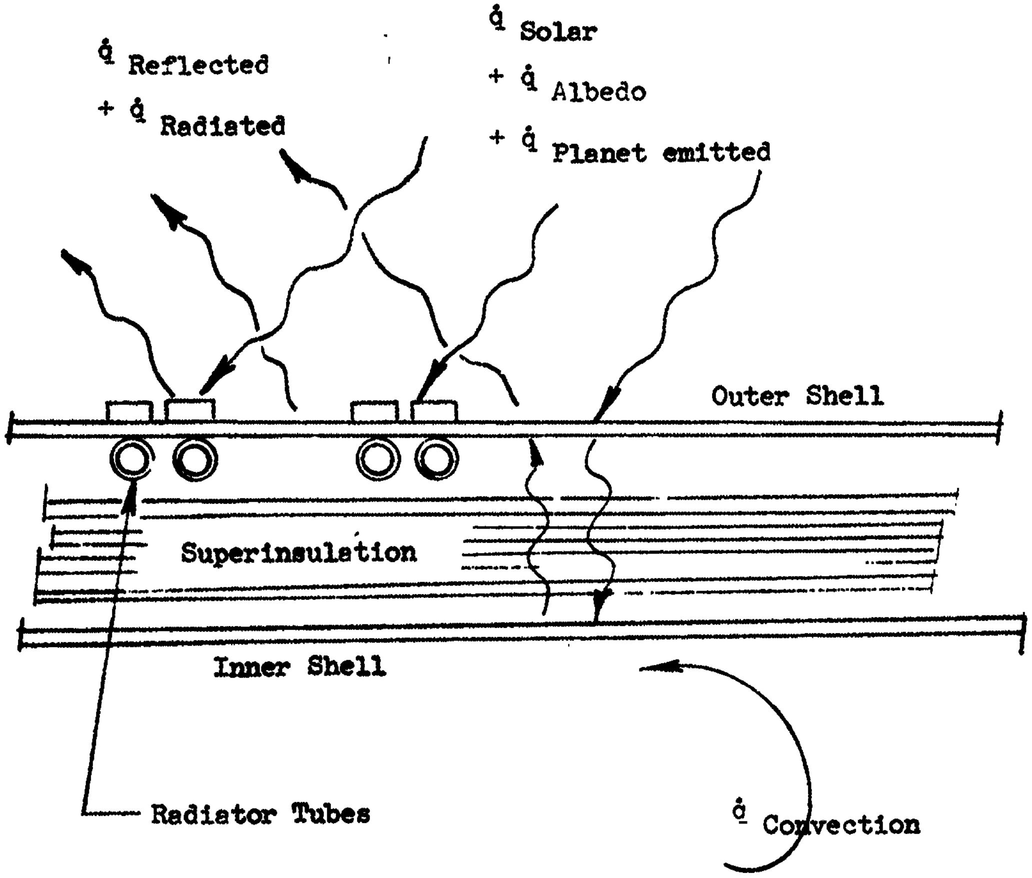


Figure 4-33. Cabin Wall Model

Using nominal values of 295°K for the cabin atmosphere temperature, 292°K for the cabin wall temperature, and the above value for the inside wall film coefficient, Equations 4-28, 4-29, and 4-30 can be combined since

$$\frac{q}{A} = h\,(T_c - T_w) = \frac{K}{L}(T_w - T_o) = \sigma \epsilon_t T_o^4$$

Then, solving for the insulation conductance, $\frac{K}{L}$,

$$\frac{K}{L} = \frac{.0366}{3.39 - \epsilon_t^{-1/4}} \qquad (4\text{-}31)$$

The computer program, however, uses the specified cabin atmosphere temperature and relative humidity in determining the value K/L from Equations 4-28, 4-29, and 4-30. Only one insulation material is considered, and that is multilayered aluminized mylar. The insulation conductances and weight data for this material are from Reference 4-50. Using these data, the equation used in the computer program to determine the total insulation material required is:

$$\text{Total weight of insulation} = \left[2.27 - 0.495\left(\ln\frac{K}{L} + 3.24\right)\right] A \qquad (4\text{-}32)$$

The outer shell environmental design conditions during orbital and interplanetary flights which affect the wall heat transfer are discussed in Subsection 3.2.2.

4.3.2 Atmosphere Cooling Equipment

The atmosphere cooling equipment, as defined in this section, is required to perform two basic tasks:

1. The removal of cabin sensible heat load, utilizing the cabin heat exchanger/fan combination.
2. The control of cabin humidity, utilizing the condenser and water separator in the gas purification loop.(*) The space suits are connected to this loop, as shown in Figure 4-34, thus enabling them to operate independently of the cabin during emergency conditions.

The computational logic considers each of the above two tasks separately. The computations for sizing the cabin heat exchanger/fan combination are

---

*Note: Also called the "Atmosphere Purification Loop" in other portions of this report and in the computational logic.

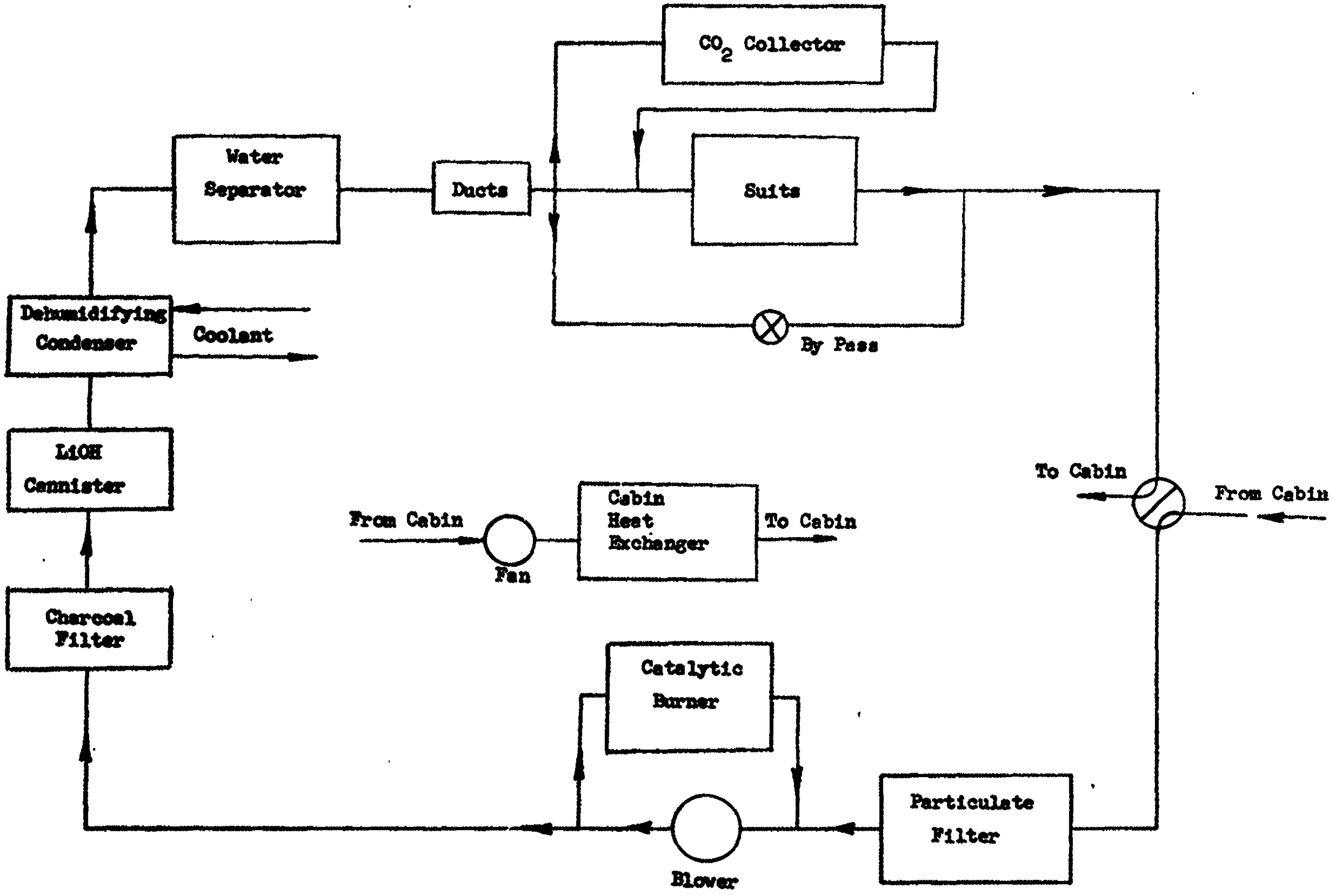


Figure 4-34. Atmosphere Cooling Equipment

straightforward. The cabin heat exchanger is tentatively configured to handle the cabin sensible heat load. A fan matching the heat exchanger is selected, and the heat exchanger/fan sizes are then determined, through an iterative process, to include the removal of the additional heat generated by the fan and motor. The cabin heat exchanger/fan combination is assumed to be inoperative during those emergency modes of operation caused by a loss of cabin atmospheric pressure, failure of liquid cooling loop, or loss of electrical power.

The procedures for obtaining the thermal and flow pressure drop balance for either normal or emergency operating conditions for the gas purification loop are essentially the same: loop flow and overall pressure drop are assumed, then thermal and flow-pressure drop determinations are made for each of the loop components, and total pressure drop is computed and compared with a previous estimate for computational convergence. Lack of convergence requires a new estimate of loop pressure drop and tentative component computations. Under normal operating conditions, the dehumidifying condenser is the major determinant in the loop flow as shown in Figure 4-34. The gas purification loop processes cabin atmosphere during normal operation and is valved to a closed suit loop during emergency periods. During normal operation, the dehumidifying condenser removes the water vapor from the cabin atmosphere at a sufficient rate to control cabin humidity at its specified level. Sensible heat is also removed in the process and this heat is included in the determination of the cabin net sensible heat load. During emergency conditions, when the gas purification loop and the suit loop are integrated, the condenser is required to remove all water vapor and sensible heat generated as well as the heat from such equipment as is included in the loop. The cooling requirements for the space suits during emergency conditions set the loop flow rate. When the normal cabin total pressure level is 0.49 kg/cm^2 (7 psia) or lower, pure oxygen at 0.25 kg/cm^2 (3.5 psia) is maintained in the emergency mode loop. For normal cabin total pressures in excess of 0.49 kg/cm^2 (7 psia), the emergency mode loop oxygen pressure of 0.49 kg/cm^2 (7 psia) is maintained. These emergency mode oxygen pressure levels have been assumed to minimize the possibility of crewmen experiencing bends following rapid transition from cabin atmospheric pressure to suit loop pressure.

The computational procedure is to determine the flow, pressure drop, and thermal balances for the loop. An LiOH unit, charcoal filter, catalytic burner, and molecular sieve/silica gel or other CO_2 collector may be included in the loop as optional units. A particulate filter is always used. These units should be basically the responsibility of the Waste Management Subsystem; however, the flow and pressure drop through the LiOH, filter, and catalytic reactor units are essentially the responsiblity of the gas purification loop. This interaction suggests that the computations be performed as a part of the atmosphere cooling equipment logic and thus in the Thermal Control Subsystem determinations. This allocation of computational responsibility has been undertaken to reduce computational iterations. The calculations for weight and volume of these units, however, are performed in the Waste Management Subsystem logic.

The analyses used in determining the sizes of the atmosphere cooling equipment components are given in the following paragraphs:

1. Cabin heat exchangers and associated fans
2. Dehumidifying condensers
3. Water separators
4. Blowers, compressors and circulation fans
5. Ducting and miscellaneous equipment

4.3.2.1 Cabin Heat Exchangers and Associated Fans

The heat exchangers and associated fans needed for spacecraft applications are very similar to those used in modern jet aircraft. A generalized Fortran program for analyzing compact heat exchangers was used to obtain parametric data for these items. This program was purchased by MDAC-WD and is entitled H723, Compact Heat Exchanger Program (Reference 4-51). The computational procedure used by this program is outlined as follows:

1. Heat exchanger effectiveness, E, is obtained;

$$E = \frac{(\dot{w}c)_h (T_i - T_o)_h}{(\dot{w}c)_{min} (T_{i,h} - T_{i,c})} = \frac{(\dot{w}c)_c (T_o - T_i)_c}{(\dot{w}c)_{min} (T_{i,h} - T_{i,c})} \qquad (4\text{-}33)$$

where,

$\dot{w}c$ = Product of flow and specific heat, kW/°K

T_i, T_o = Inlet and outlet temperatures, °K

subscripts

h = Hot side

c = Cold side

min = minimum value

2. The number of heat transfer units, NTU, is determined. Tabular data relating effectiveness, E, to $(\dot{w}c)_{min}/(\dot{w}c)_{max}$ and NTU for individual heat exchanger configurations (such as cross-flow with both fluids unmixed) are provided in the computer program.

3. The overall heat exchanger conductance UA is determined from the relationship,

$$UA = NTU\ (\dot{w}c)_{min}\ \frac{kW}{°K} \tag{4-34}$$

4. Pressure drops are initially estimated but later are determined by iterative computations.

5. Reynolds numbers, Re, for each side of the heat exchanger are initially estimated but are later determined by iterative computations.

$$Re = \frac{G\ D_h}{3600\mu} \tag{4-35}$$

where,

G = Flow per unit flow area, $\frac{kg}{hr\ m^2}$

D_h = Hydraulic diameter, m

6. **The Colburn heat transfer factor, j, and friction factor, f, are computed from j and f versus Reynolds number relationships for the particular heat exchanger being considered.**

7. **Heat transfer coefficients, h, and heat transfer fin effectiveness, η_f, values are computed from coolant fluid properties, heat exchanger matrix geometry, matrix material properties, flow rates, and j values.**

$$h = \frac{G\ j\ c}{Pr^{2/3}},\ \frac{kW}{m^2\ °K} \tag{4-36}$$

$$\eta_f = 1 - \frac{A_f}{A}\left[1 - \frac{\tanh \bar{\ell}\sqrt{2h/K_f\Delta_f}}{\bar{\ell}\sqrt{2h/K_f\Delta_f}}\right] \qquad (4\text{-}36a)$$

dimensionless

where,

A_f = Fin surface area, m^2

A = Heat transfer area, m^2

Δ_f = Fin thickness, m

$\bar{\ell}$ = Half fin length between plates, m

8. Heat transfer areas and flow lengths, L, are computed from heat exchanger properties, flow rates, Reynolds numbers, heat transfer coefficients, heat transfer effectivenesses, and UA.

$$\frac{1}{UA} = \left(\frac{1}{\eta hA}\right)_h + \left(\frac{1}{\eta hA}\right)_c \qquad (4\text{-}37)$$

(Reynolds numbers specify flow cross-sectional areas. Flow cross-sectional areas are related to heat transfer areas and flow lengths for specified matrices.)

9. Pressure drops are computed from flow lengths, flow rates, and friction factors.

$$\Delta P = \left(\frac{4fL}{D_h} + K_E\right)\frac{G^2}{2g_c\,\rho_f},\ \frac{kg}{m^2} \qquad (4\text{-}38)$$

where K_E is a factor which accounts for miscellaneous pressure drop effects such as occur at entrances and exits.

10. **Computed pressure drops are compared with previous values for pressure drop and new estimates for Reynolds numbers are provided if the comparison so indicates. New values for Reynolds numbers require a return to step 5.**

11. **With convergence of Reynolds numbers, the heat exchanger core characteristics of volume and weight are computed from the required face area, heat exchanger length, and matrix densities.**

The following assumptions were made in the use of the H723 computer program to obtain parametric data for cabin heat exchangers:

1. Crossflow fin and plate configuration with one pass on gas side and two passes on liquid side.
2. Core geometry dimensional ratios:

$$\frac{L_{gas}}{L_{no\ flow}} \geq \frac{1}{3} \qquad \frac{L_{gas}}{L_{liquid}} \geq \frac{1}{6}$$

   where,

   L_{gas}, L_{liquid}, and $L_{no\ flow}$ are the core lengths in the subscripted directions.
3. Core matrices similar to those used in Apollo cabin heat exchanger, i.e., rectangular offset fins with double fin set on gas side, have the following physical characteristics:

	Heat transfer area/Hx volume (ft^2/ft^3)	Fins per Inch	Plate Spacing (in.)	Offset (in.)	Fin Thickness (in.)	Material
Gas side	448	16	0.153	0.147	0.002	Copper
Liquid side	131	20	0.050	0.100	0.002	Stainless steel

and the following heat transfer and friction coefficients:

$$\text{Gas side} \quad \begin{cases} j = 1.18\ Re^{-0.64} \\ f = 7.15\ Re^{-0.734} \end{cases}$$

$$\text{Liquid side} \quad \begin{cases} j = 0.243\ Re^{-0.438} \\ f = 5.56\ Re^{-0.631} \end{cases}$$

These coefficients as defined in detail in Reference 4-52 are:

$$j = St\ Pr^{2/3} = \left(\frac{h}{Gc_p}\right)\left(\frac{\mu}{c_p k}\right)^{2/3} \tag{4-39}$$

$$f = \frac{\tau_s}{\left(\rho V^2/2g_c\right)} \tag{4-40}$$

where,

St = Stanton number

Pr = Prandtl number

Re = Reynolds number

h = Heat transfer coefficient, $\frac{kW_t}{m^2\ ^\circ K}$

G = Mass flow per unit area, $\frac{kg}{hr\ m^2}$

c_p = Specific heat at constant pressure, $\frac{kW_t\text{-}hr}{kg\ ^\circ K}$

μ = Fluid viscosity, kg/m hr

K = Fluid thermal conductivity, $kW_t/m\ ^\circ K$

τ_s = Wall shear per unit area, $\frac{kg_f}{m^2}$

ρ = Fluid density, $\frac{kg}{m^3}$

V = Fluid velocity, $\frac{m}{hr}$

g_c = Proportionality factor in Newton's second law of motion, $\frac{m}{hr^2} \frac{kg_m}{kg_f}$

4. Heat exchanger density = 610.0 kg/m^3 (38 lb/ft^3)
5. Coolant inlet temperature = 286°K (55°F)
6. Gas outlet temperature = 289°K (60°F)
7. Gas inlet temperatures for individual cabin atmosphere constituent combinations and pressure levels are the average of the values given in Table ?-6.

The results of the parametric analyses of cabin heat exchangers and their fans resulted in heat exchanger weights which were considerably lighter than corresponding actual units for the Apollo and Gemini programs. The discrepancy is probably due to conservative design practices, inadequacy of the theory for very small units where end effects and thermal isolation become important, and lack of available heat transfer data at the low gas side Reynolds numbers found to be propitious. The actual and theoretical heat exchangers weights were found to have a ratio of approximately 7. Since the weights and corresponding volumes involved are comparatively small compared to these types of data for other life support equipment the computed and presented heat exchanger weights and volumes were increased by the factor of 7. The computed fan power terms were found to be in good agreement with corresponding power terms for actual units so the computed powers are presented here.

These results for cabin heat exchangers and fans are shown in Figures 4-35 through 4-39. These data give the heat exchanger weight, volume, and

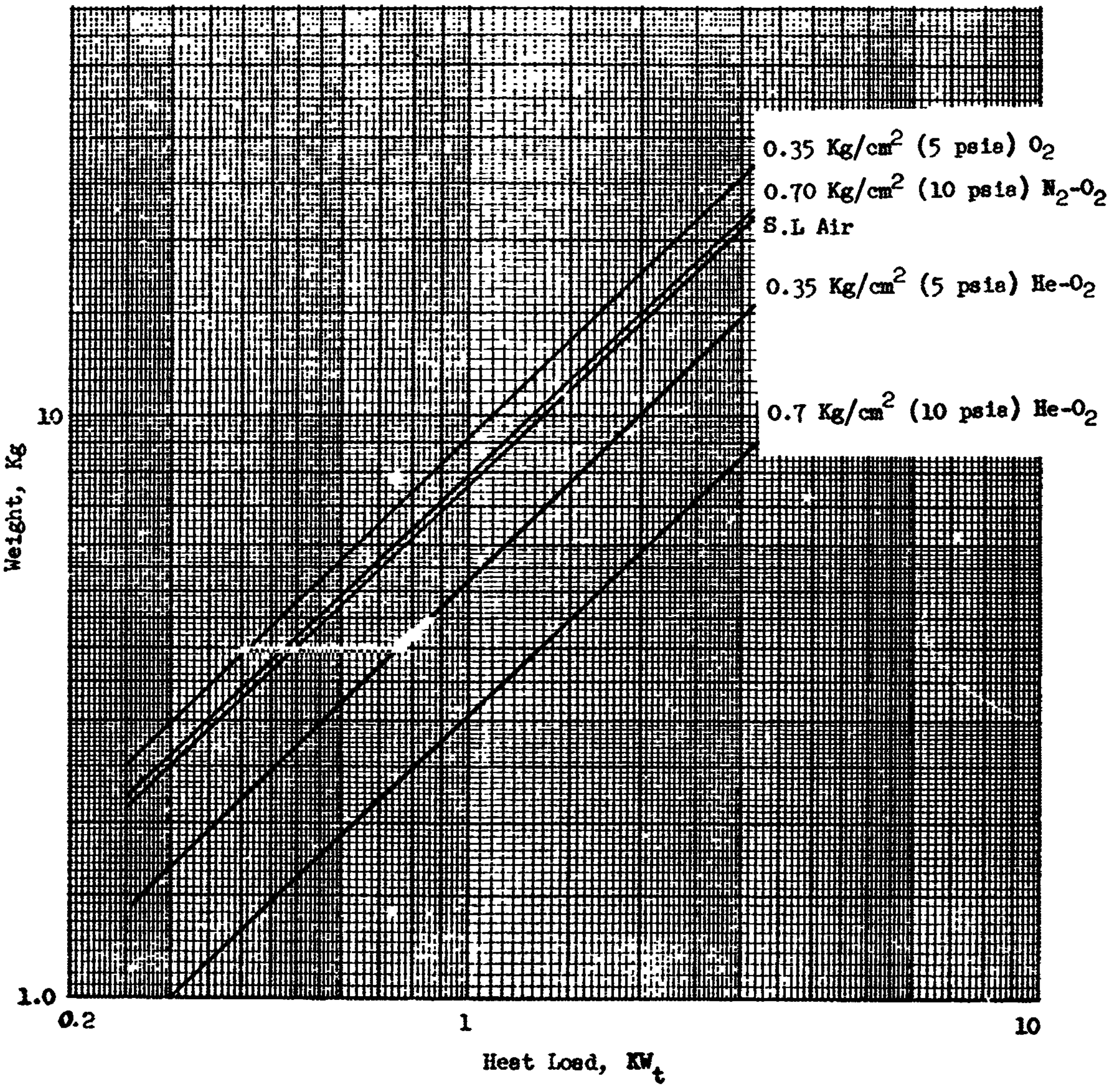


Figure 4-36. Cabin Heat Exchanger Core Weight

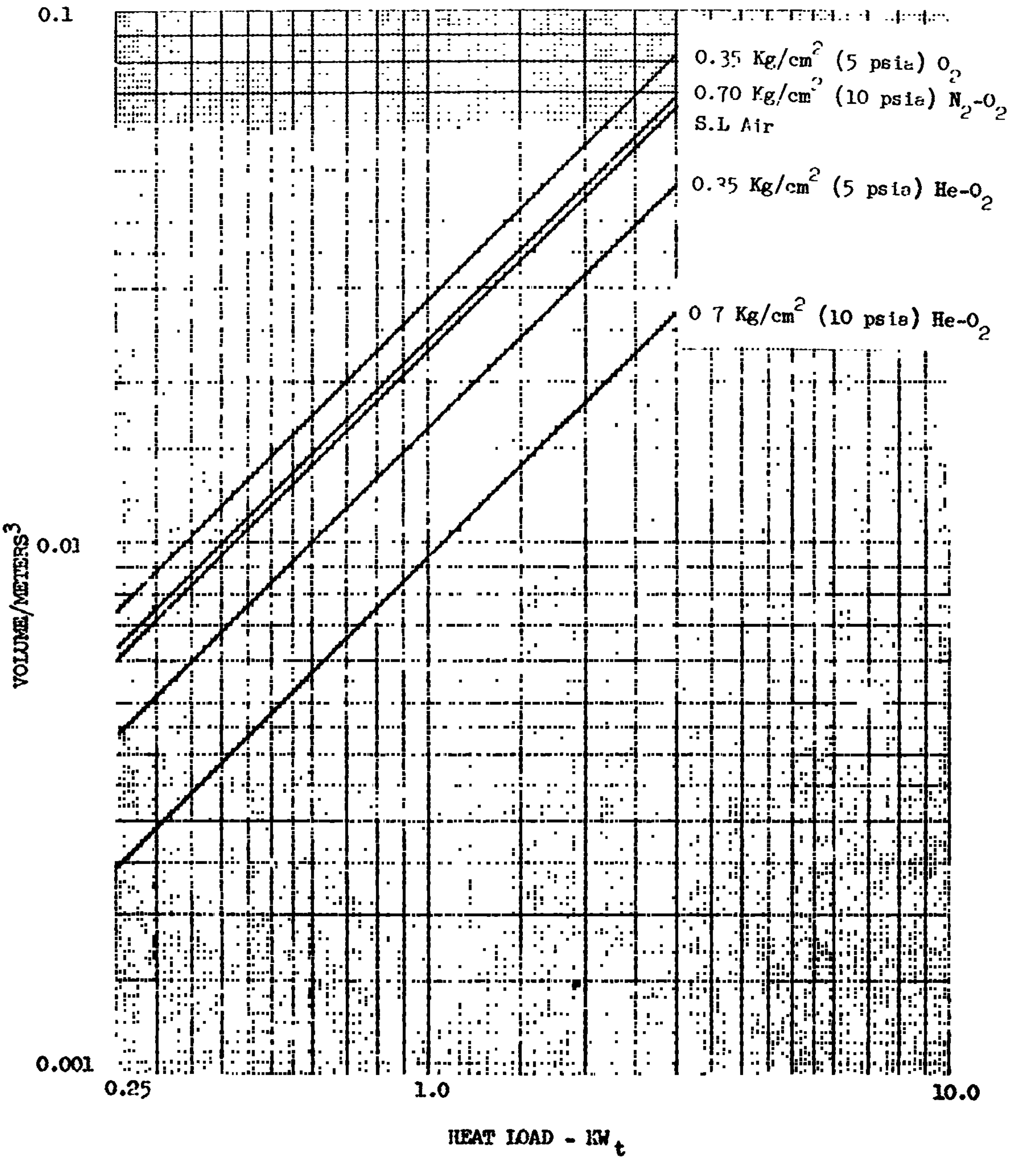


Figure 4-36. Cabin Heat Exchanger Core Volume

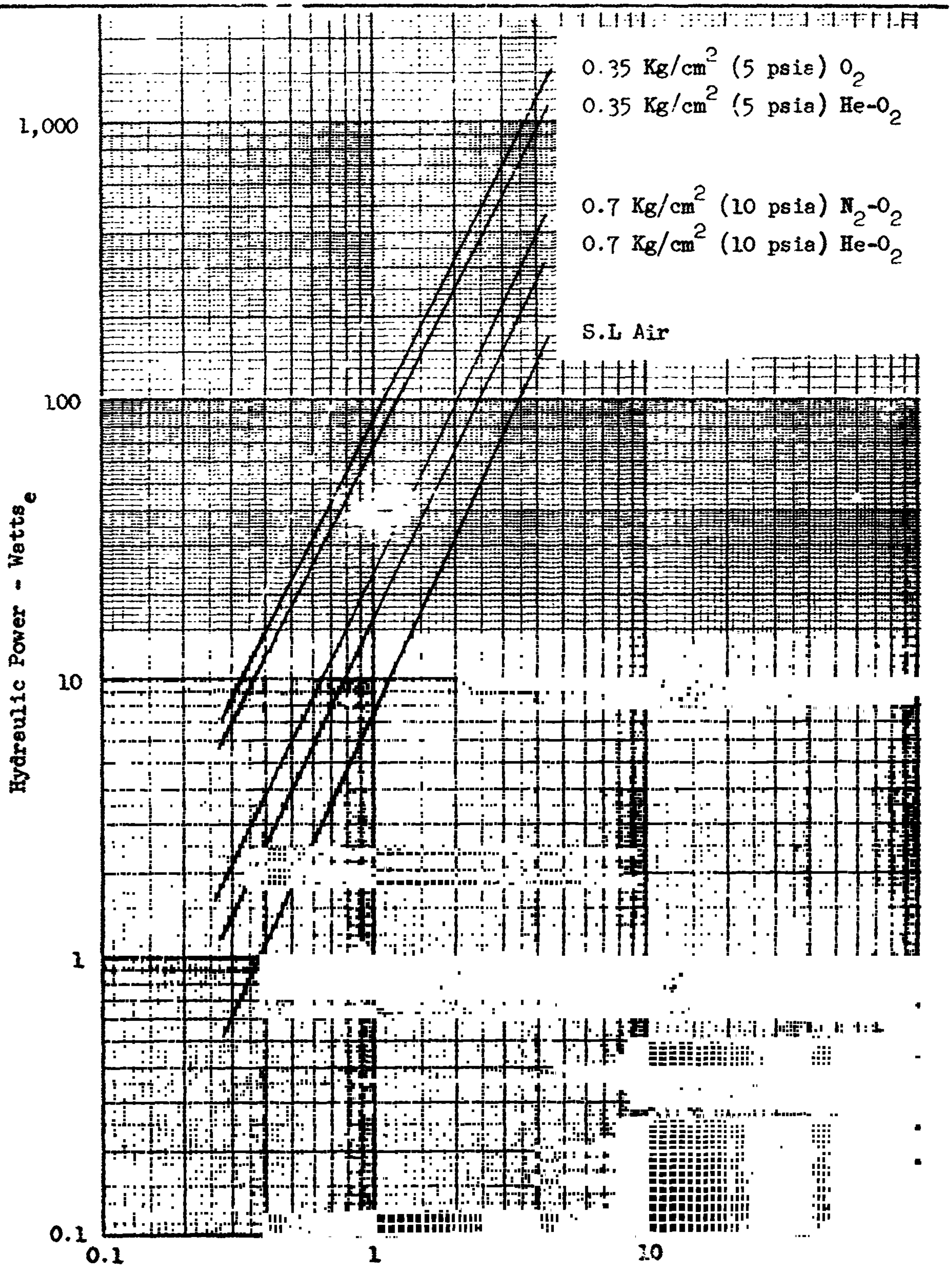


Figure 4-37. Cabin Heat Exchanger Hydraulic Power Requirements

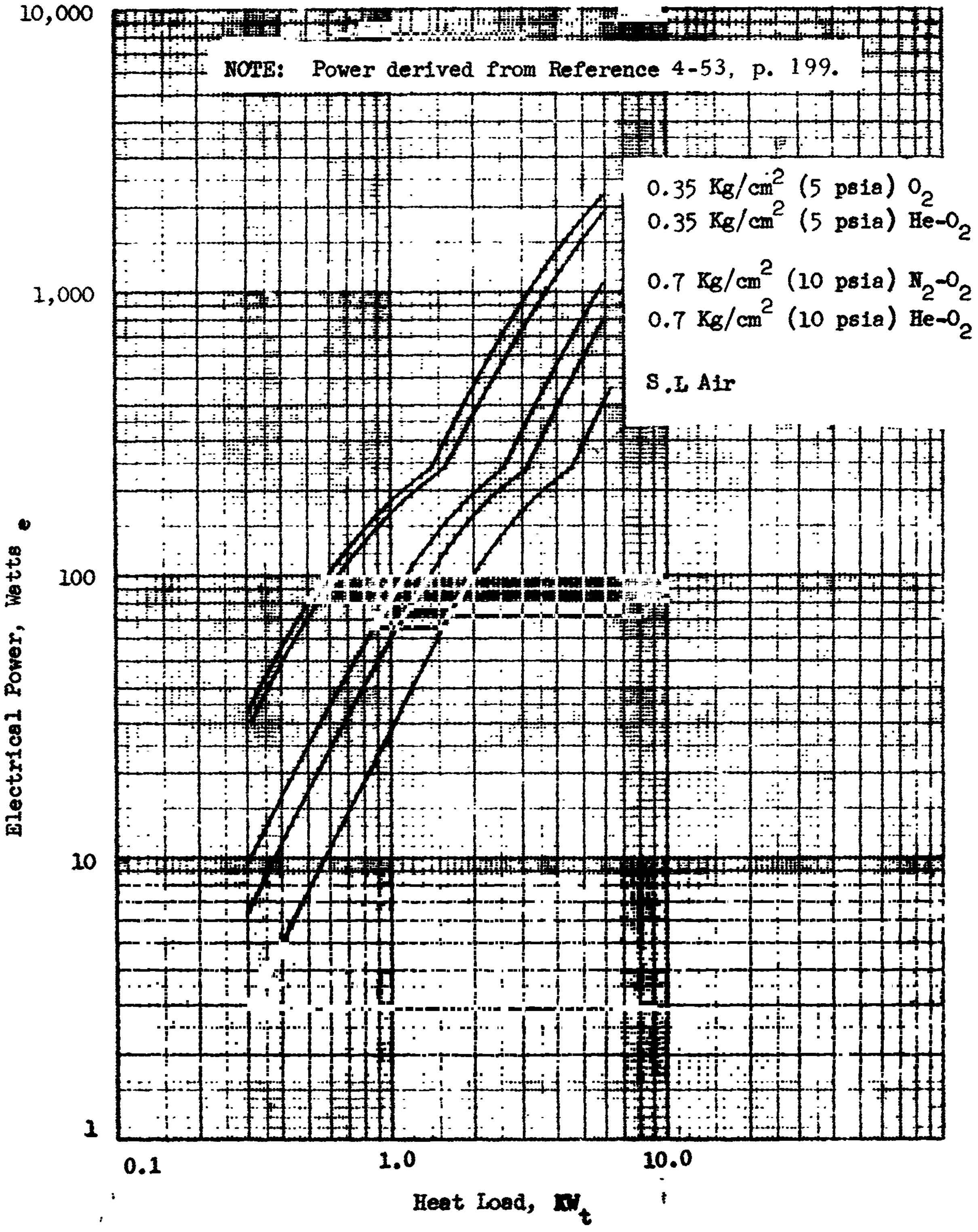


Figure 4-38. Cabin Heat Exchanger Fan Electrical Power Requirement

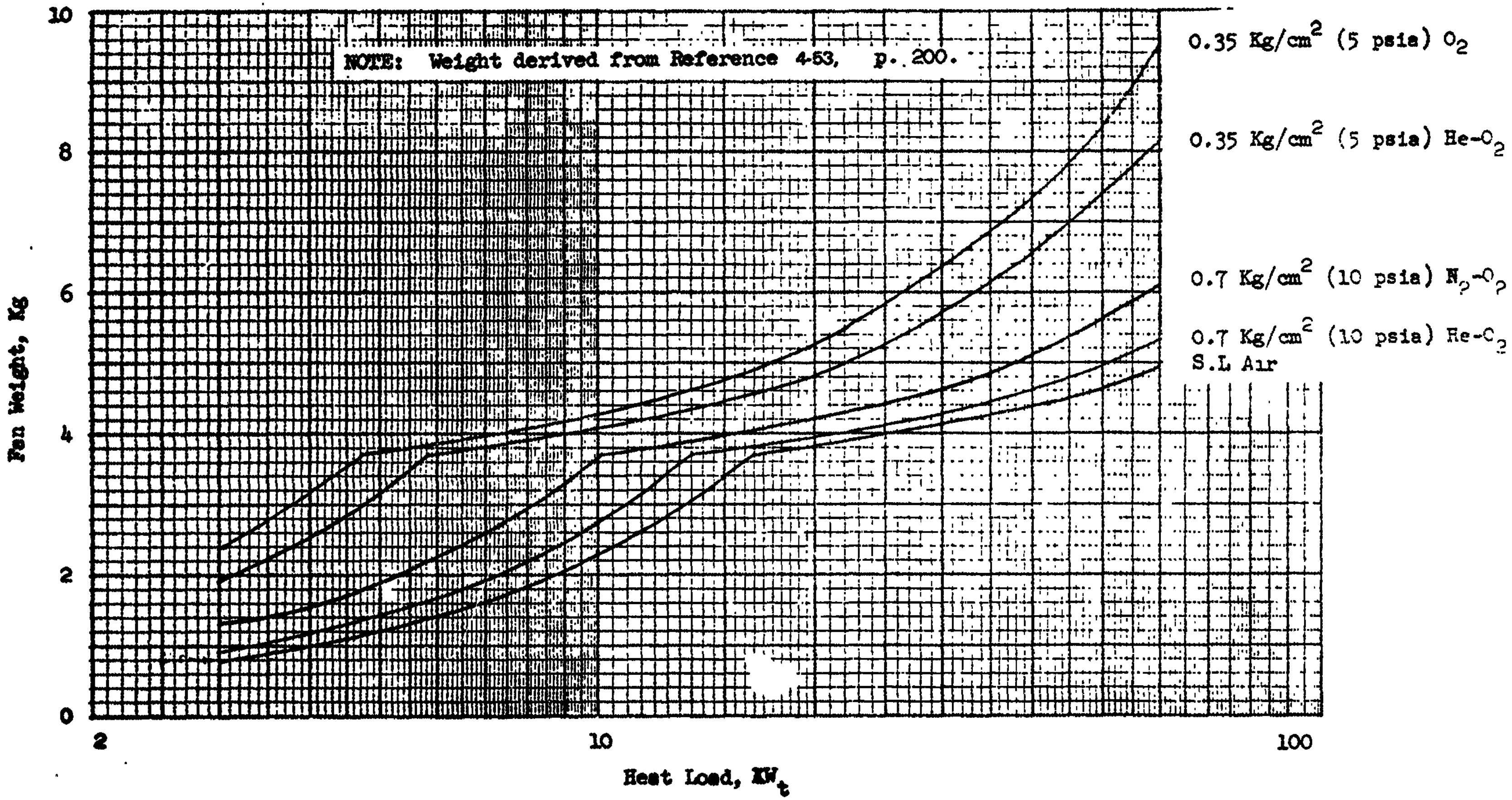


Figure 4-39. Cabin Heat Exchanger Fan Weight

electrical power required and the fan characteristics for several types of cabin atmospheres.

4.3.2.2 Dehumidifying Condensers

Dehumidifying condensers are included in the gas purification loops as well as in various assemblies which separate moisture from gas. The purification loop condensers have been analytically designed and the remaining condensers have been parameterized empirically.

During normal operation, the purification loop condenser is required to control cabin humidity level and to remove sensible heat loads and water vapor loads generated by other equipment in the loop. During emergency operation, with the gas purification loop in the closed loop mode, the condenser is required to perform a similar function including controlling the humidity level in the space suits. The condenser size is determined for each of the normal and emergency conditions. The larger size is considered to be the required unit. The condenser design conditions of gas inlet temperatures and water vapor content have a rather broad range. The following assumptions have been used in sizing these condensers:

1. Counterflow fin and plate configuration with one pass on each side.
2. The gas and liquid flow lengths are equal.
3. Core weight is directly proportional to product of overall heat transfer coefficient and heat exchanger area (UA). (Value based on existing spacecraft designs of condenser weight = 45.5 UA, kg, where (UA) is in terms of $kW_t/°K$).
4. Pressure drop on gas side = 0.00051 kg/cm^2
5. Pressure drop on liquid size = 0.035 kg/cm^2
6. Core density = 610.0 kg/m^3 (38 lb/ft^3)

7. Coolant inlet temperature = 278°K (40°F)

8. Gas outlet temperature = 284°K (50°F)

The computational procedure used for dehumidifying condensers is as follows:

1. The condenser effectiveness, E, is obtained from:

$$E = \frac{T_{i,h} - T_{o,h}}{T_{i,h} - T_{i,c}} \tag{4-41}$$

where

$T_{i,h}$ = temperature of hot fluid in, °K

$T_{o,h}$ = temperature of hot fluid out, °K

$T_{i,c}$ = temperature of cold fluid in, °K

2. Based on the equation for counterflow condensers, the number of heat transfer units, NTU, are determined for each side of the condenser.

$$NTU_g = \frac{1}{1 - z} \ln \frac{Ez - 1}{E - 1} \tag{4-42}$$

$$NTU = NTU_g \times z \tag{4-43}$$

where

z = capacitance ratio $\dot{w}_g \, c_{p,g} / \dot{w}_\ell \, c_{p,\ell}$

$\dot{w}$ = mass flow rate, kg/hr

c_p = specific heat, kW_t/hr/kg °K

subscripts

g = gas

ℓ = liquid coolant

3. The product of overall heat transfer coefficient and condenser area is calculated from number of heat transfer units, gas flow rate and gas specific heat

$$UA = NTU \times c_{p_g} \times \dot{w}_g \qquad (4\text{-}44)$$

4. Condenser weight and volume are calculated from UA as follows:

$$W_{hx} = 45.5 \times UA \qquad (4\text{-}45)$$

$$V_{hx} = W_{hx}/\rho_{hx} \qquad (4\text{-}46)$$

where

W_{hx} = heat exchanger weight, kg

V_{hx} = volume of heat exchanger, m^3

ρ_{hx} = heat exchanger density, kg/m^3

4.3.2.3 Water Separator

Only one type of condensate water separator is used in this study, and that is the hydrophobic-hydrophilic type of water separator. Data for a range of sizes for operating units were scaled from existing units keeping a constant value of face velocity of incoming gas. A constant length-to-diameter ratio is also maintained. As face velocity and angle of internal core are expected to be the primary factors affecting the water separator performance, the scaled versions of the separator should have the same performance characteristics as the existing units. The following scaling laws are the result of the above procedure.

$$W_{sep} = 0.003\ (\dot{w}/\rho)^{3/2},\ \text{kg} \tag{4-47}$$

$$V_{sep} = 5.59 \times 10^{-6}\ (\dot{w}/\rho)^{3/2},\ \text{m}^3 \tag{4-48}$$

$$\Delta P = 0.0556\rho,\ \text{kg/cm}^2 \tag{4-49}$$

where

W_{sep} - weight of separator, kg

V_{sep} - volume of separator, m^3

$\dot{w}$ - weight flow of gas, kg/hr

ρ - density of gas, kg/m^3

ΔP - pressure drop, kg/cm^2

The expendable requirements, if any, are not well defined, for insufficient data are available to determine if insert replacement will be necessary after long periods of use.

4.3.2.4 Blower, Compressors and Circulation Fans

Figure 4-34 shows that the gas purification loop serves the dual purpose of purifying the cabin atmosphere during normal operation and ventilating the pressure suits during emergency operation. Since the flow and pressure drop requirements are considerably different for these two modes of operation, a blower is used during normal operation and a compressor is required during emergencies. The efficiency, weight and volume of compressors and blowers were obtained from Reference 4-53 and the data are summarized below.

$$\text{for } P_i > 0.125 \text{ kW}, \quad \eta = 0.164\, P_i + 0.48 \tag{4-50a}$$

$$\text{for } P_i < 0.125 \text{ kW}, \quad \eta = 2.72\, P_i + 0.16 \tag{4-50b}$$

$$\text{for } \dot{Q} < 615 \frac{\text{m}^3}{\text{hr}}, \quad W = 0.227 + 0.0055\, \dot{Q}, \text{ kg} \tag{4-51a}$$

$$\text{for } \dot{Q} > 615 \frac{\text{m}^3}{\text{hr}}, \quad W = 3.0 + 0.001\, \dot{Q}, \text{ kg} \tag{4-51b}$$

$$V_c = 0.0025\, W, \text{ m}^3 \tag{4-52}$$

$$V_b = 0.0043\, W, \text{ m}^3 \tag{4-53}$$

where

P_i - ideal power, kW_e

η - blower or compressor efficiency

$\dot{Q}$ - volumetric flow, m^3/hr

W - weight of blower or compressor, kg

V_c - volume of compressors, m^3

V_b - volume of blower, m^3

Fans produce circulation of vehicle atmosphere, under normal conditions to aid in crew and equipment cooling and to avoid atmosphere stagnation under zero gravity conditions. This type of far should have low weight and require little power while operating in an unloaded condition. Since most early manned spacecraft were designed for space-suited operation, development of space type free-flow fans has not received major attention. But, one such fan has been developed for the Manned Orbital Laboratory (MOL), based on some highly efficient nonflight type units which have been built. For medium sized free-flow fans, a flow to power ratio of about 80 cfm per $watt_e$ seems to be practical. Based on this value, the equations for the free-flow fan characteristics are:

$$W_{fan} = 0.1185\ V_{cab},\ \text{kg} \tag{4-54}$$

$$V_{fan} = 5.4 \times 10^{-4}\ V_{cab},\ m^3 \tag{4-55}$$

$$P_{fan} = 6.23 \times 10^{-4}\ V_{cab},\ \text{kW} \tag{4-56}$$

where

W_{fan} - weight of fans, kg

V_{fan} - volume of fans, m^3

P_{fan} - power of fans, kW

V_{cab} - volume of occupied cabin, m^3

4.3.2.5 Ducting and Miscellaneous Equipment

The gas flow through the purification loop is carried between components by ducting. Selecting a ducting diameter is critical because appreciable weight compensations are involved in blower weight and power required for gas flow compared to the weight and volume requirements of the duct. A weight trade-off analysis was performed to select a duct diameter that represents minimum weight. The following assumptions were used:

1. Turbulent flow
2. Two ducting bends per meter of length
3. Blower power weight penalty = 500 lb/kW$_e$
4. Vehicle volume weight penalty = 1 lb/ft^3
5. Duct length = 6 m

Using these above assumptions, the following equations result for ducting characteristics.

$$D_d = 0.026 \times (\dot{w})^{.42}/\rho^{0.14}, \ \mathrm{m} \qquad (4\text{-}57)$$

$$V_d = (3\pi/2)\, D_d^2, \ \mathrm{m}^3 \qquad (4\text{-}58)$$

$$W_d = 0.03 + 39.5\, D_d, \ \mathrm{kg} \qquad (4\text{-}59)$$

where

D_d - duct diameter, m

$\dot{w}$ - gas flow, kg/hr

ρ - gas density, kg/m^3

V_d - duct volume, m^3

W_d - duct weight, kg

The miscellaneous equipment necessary for instrumentation, control and packaging of the purification loop were assumed to be: (1) sensors, (2) check valves, (3) suit connectors, (4) bypass valves, (5) vent valves, and (6) switches. This list was obtained from Reference 4-53. Items such as sensors and switches do not require scaling, but equipment such as suit connectors and valves must be scaled. These miscellaneous equipment scaling equations are:

$$W = 5.05 + 4.56\ N,\ \text{kg} \tag{4-60}$$

$$V = 1.25 \times 10^{-2} + 9.05 \times 10^{-3}\ N,\ \text{m}^3 \tag{4-61}$$

where

W = weight of miscellaneous equipment, kg

N = number of crew members

V = volume of miscellaneous equipment, m^3

4.3.3 Liquid Cooling and Heating Loops

Heat generated by crewmen and life support system components is transferred through heat transfer surfaces to a liquid coolant. The coolant is then circulated to the space radiator where the heat is rejected. The fluid, tubing, pumps, valves, and other equipment involved in transporting heat from the cooled equipment to the space radiator is referred to as cooling circuitry or as the cooling loop.

In developing the modes of operation for the cooling circuitry it was originally planned to have the option of a single loop or a double loop with an interface heat exchanger between the two loops. A sensitivity analysis subsequently indicated that the double-loop arrangement generally has the lower effective weight. Effective weight is defined as the sum of all the fixed weight plus the equivalent weight of the electrical power to supply the pumping power. On the basis of this analysis, the option was eliminated and only the double loop arrangement has been parameterized. The loop connecting the component heat transfer surfaces and the interface heat exchanger is entirely within the vehicle, and its heat transfer fluid is assumed to be water. For this study, this loop is referred to as "the cooling loop". The loop connecting the interface heat exchanger and the space radiator is called the radiator loop. Since its heat transfer fluid faces a greater temperature range, Freon 21 is used as the fluid. Figure 4-40 is a schematic of the cooling and radiator loops.

In addition, a heating loop is provided within the vehicle for transferring heat to those life support system components which require same. An electrical source is used for this purpose. Typical components which use heat from a liquid heating loop include molecular sieve/silica gel CO_2 collectors, water heaters, and water evaporators in air evaporation water recovery units. Other sources of heat may include waste heat from radioisotope dynamic cycle power systems, or radioisotope heaters. Water is the assumed heat transport fluid in this loop. Figure 4-41 is a schematic of the heating loop.

The cooling and the heating loops generally interface with components which operate at significantly different temperature levels. The differences in individual contributions to cooling and heating loads for these components are

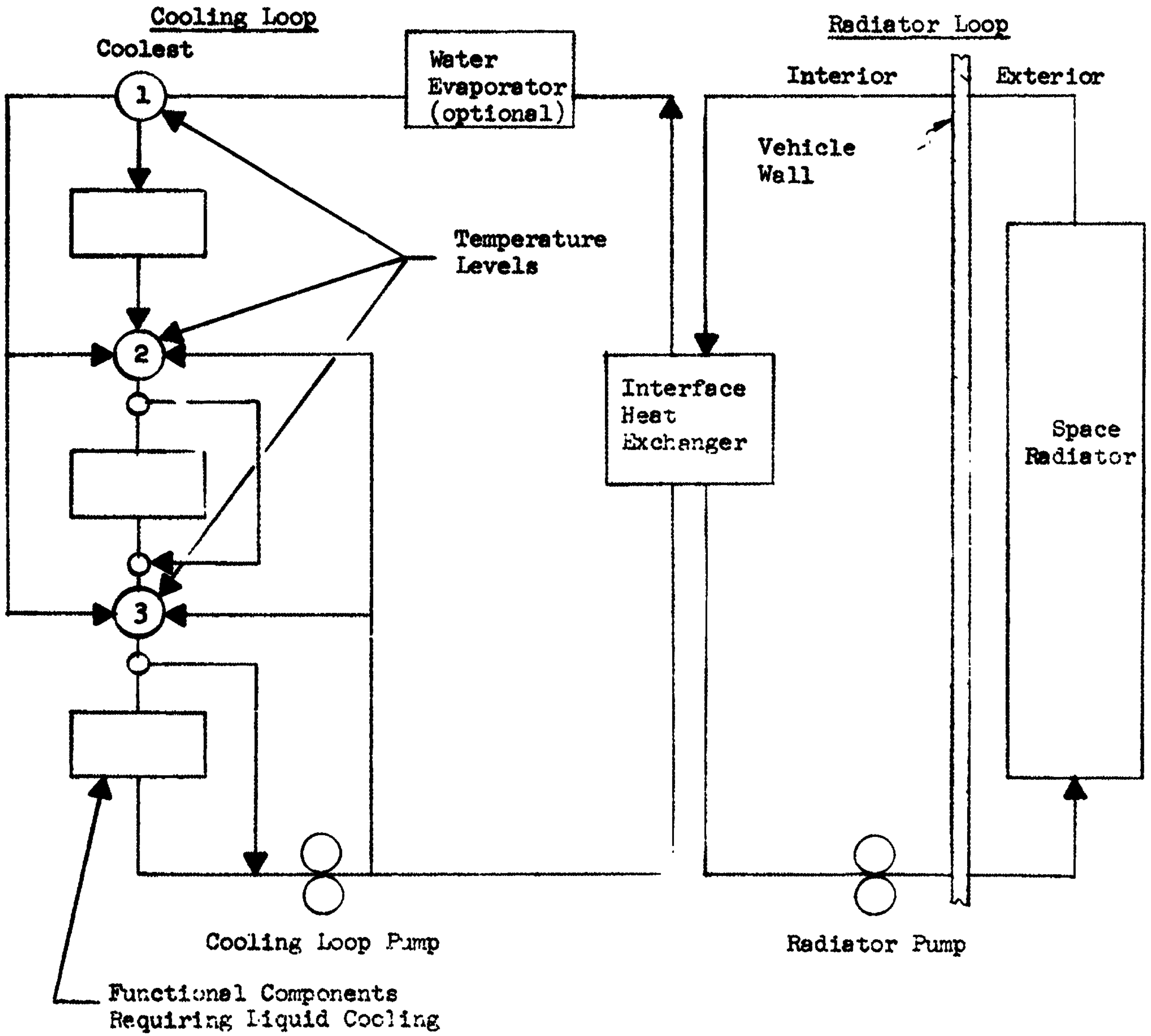


Figure 4-40. Cooling and Radiator Loops

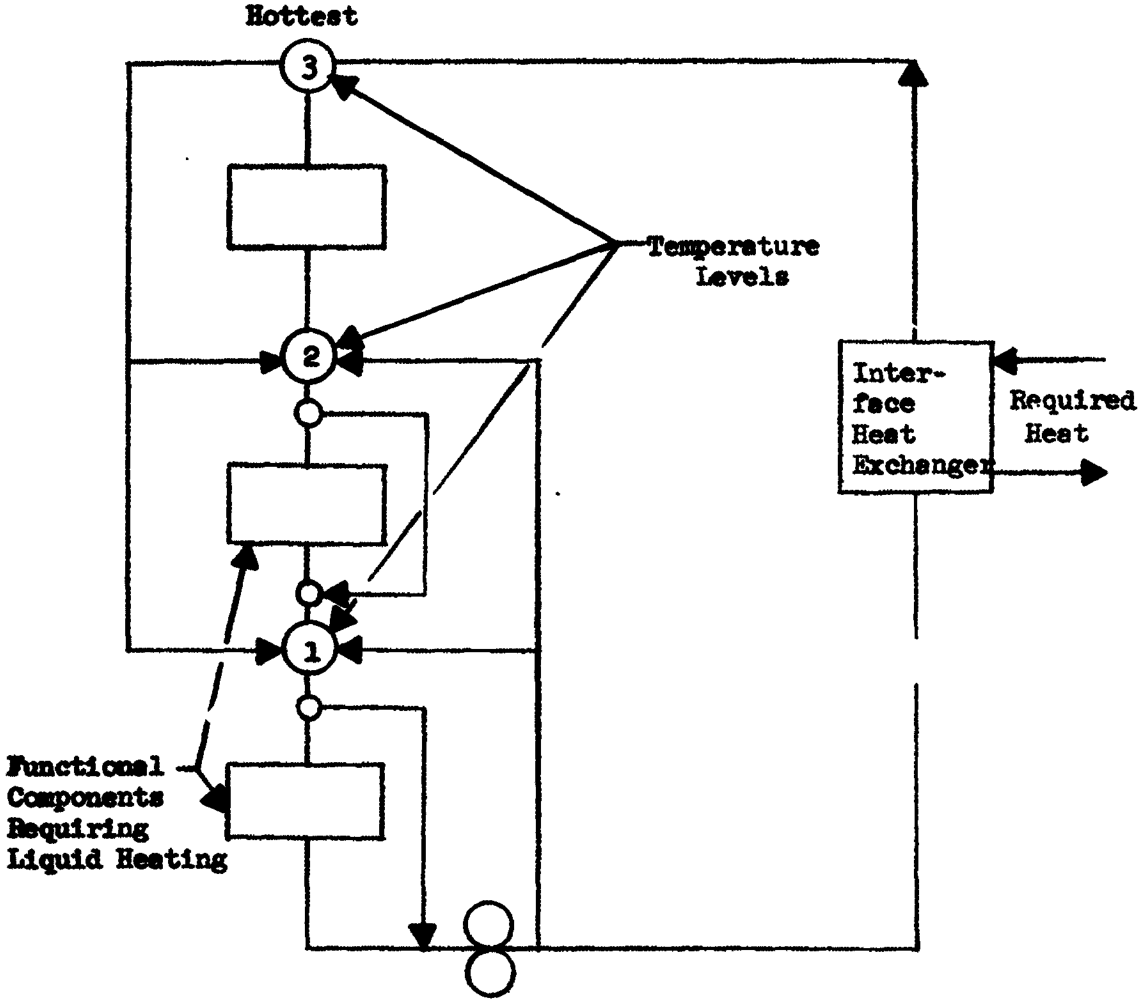


Figure 4-41. Heating Loop

also often quite significant. These differences require corresponding differences in flow rate and fluid temperature change at each of the component heat transfer surfaces. Design analyses of these loops for real spacecraft entail determinations of the best compromise arrangements for parallel and series interconnecting fluid flow between the various systems and components. It is desirable to minimize pumping power and fluid tubing fixed weight. Increasing reliability, maintainability, and compatibility with off-design point operations are also desirable.

For purposes of this study, the plumbing circuits for the cooling and heating loops have been simplified. These circuit arrangements allow one of three temperature levels to be specified as the operating inlet temperature level for individual components. All components requiring a given coolant fluid temperature level are considered to be arranged in parallel and make up one of the temperature level groups. The resulting total flow rate and mix temperature at the outlet of this group of components are compared with the required total flow rate and specified temperature level for the next lower temperature and downstream group of components. Lack of agreement between these quantities of cooling fluid required between two adjacent temperature levels is reconciled by bypassing flow and/or augmenting flow with an appropriate mixture of inlet and outlet flows. The individual component pressure drops at each temperature level are compared to determine the maximum value. As the components at each temperature level are in parallel, the maximum pressure drop establishes the loop pressure drop for the particular temperature level. Some type of flow restriction devices is assumed to be used in conjunction with all components which have pressure drops below the maximum value. The three maximum pressure drops, corresponding to the three temperature levels, are summed and determine the portion of loop pressure drop across the entire included group of cooled components. Pressure drops due to tubing, tubing connections, and valving are provided by a scaling law and the total loop pressure drop is determined by summing these values with the summed maximum group pressure drops. The fluid, tubing, and pump weights and the pump electrical power may then be determined.

The emergency cooling equipment is comprised of the water evaporator, steam vent, water supplies, and controls. The emergency cooling loop is shown schematically in Figure 4-42.

In the detailed discussion which follows, there are given the assumptions, engineering designs and component characteristics for the development of the following heating and cooling system units:

1. Space Radiators
2. Water Evaporator
3. Cold Plates
4. Interface Heat Exchanger
5. Cooling and Heating Loop Tubing
6. Liquid Circulation Pumps

4.3.3.1 Space Radiator

Present and planned future manned space vehicles have used portions of the vehicle outer shell as the radiating surface for, or the support for, a space radiator such as for the life support system. Operating temperature levels

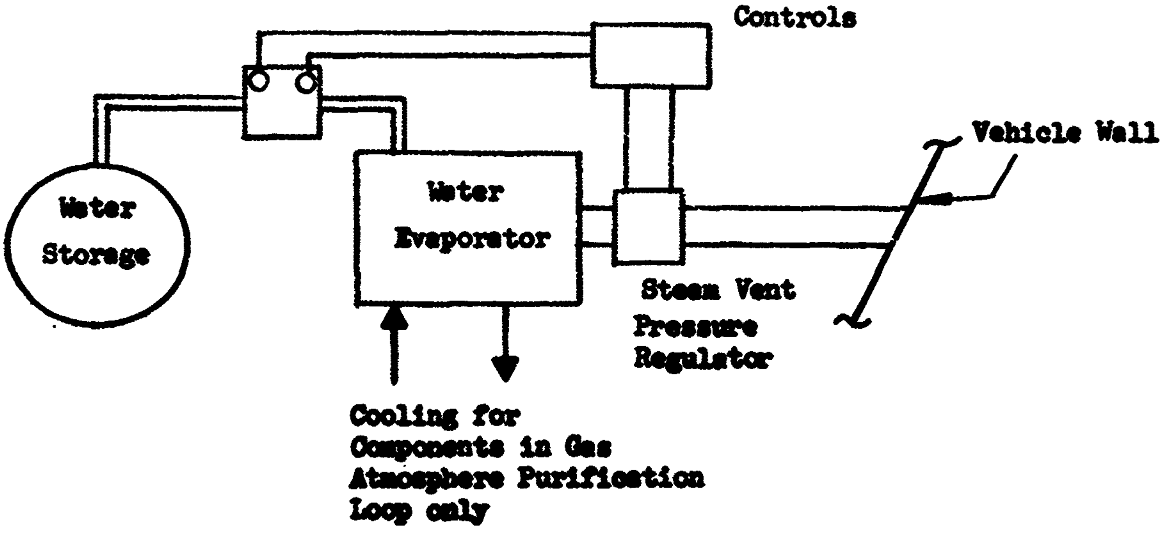


Figure 4-42. Emergency Cooling Equipment

for the radiator fluid, radiative properties of surface coatings, structural and fluid heat transfer characteristics, characteristics of the external thermal environment (solar heating, albedo, and planetary emitted radiation), and vehicle surface area available for radiators have been found to be compatible with radiator systems that include sets of small diameter fluid transfer tubes attached to the vehicle outer shell. Headers, internal plumbing to heat transfer surfaces, pumps, controls, and tubes, comprise each radiator loop. Deployable radiators aimed at supplementing the outer shell type radiator have had some consideration. There is generally sufficient vehicle surface area available for use as the radiator surface. The space radiator evaluations for the Manned Orbital Research Laboratory (MORL) indicated a relatively small deficiency in desired and available vehicle surface area (Reference 4-49). For that study the additional required area was obtained by lengthening the vehicle sufficiently to obtain the desired amount. A supplementary deployable radiator for the MORL was evaluated and would have required less additional surface area. Many unresolved features of deployable radiators include items such as deployment mechanism requirements, flexible fluid line requirements, structural requirements, and interaction with space docking and extravehicular activities. For this study, deployable space radiator systems have not been parameterized nor included. The required supplementary radiator area is considered to be achieved through a lengthening of the vehicle structural shell and when this occurs the weight of this additional vehicle structure is included, as an incremental weight, in the total radiator loop weight.

Since meteoroid flux presents a significant hazard to space radiators, the required meteoroid bumper thickness is determined and is compared to the combined thickness of the vehicle outer shell and the tube wall. When indicated, the required meteoroid bumpers are added and their weight included with the radiator loop. Because meteoroid puncture is so serious in the radiator loop, there has been assumed to be one active and one redundant set of tubes, headers, and internal plumbing circuitry included in the radiator loop configuration components. This redundant loop has been included in order to increase the reliability of the unit. The meteoroid flux and penetration models specified in Subsection 3.2.3 are used in determining the meteoroid bumper requirements.

The configuration thus selected for the life support system space radiator consists of two sets of adjacent supply and return fluid headers oriented parallel to the longitudinal vehicle axis and two sets of parallel radiator tubes which traverse the circumference of the vehicle (see Figure 4-43). The headers are located within the structural wall and the tubes are assumed to be attached to the outer shell of the vehicle as shown in detail on the upper portion of Figure 4-43. The tubes may make one or more passes around the vehicle circumference depending upon the radiator sizing requirements. The surface area of the vehicle available for use as a space radiator is used in initial radiator sizing computations.

Space radiator studies have indicated the advantages of the circumferential tube radiator configurations for applications on Earth orbital space vehicles (References 4-54 and 4-55). The circumferential tube orientation is favored instead of the axial tube orientation because the effects of variations in environmental thermal conditions around the vehicle circumference tend to be averaged by flow in this type of radiator. This feature also lends

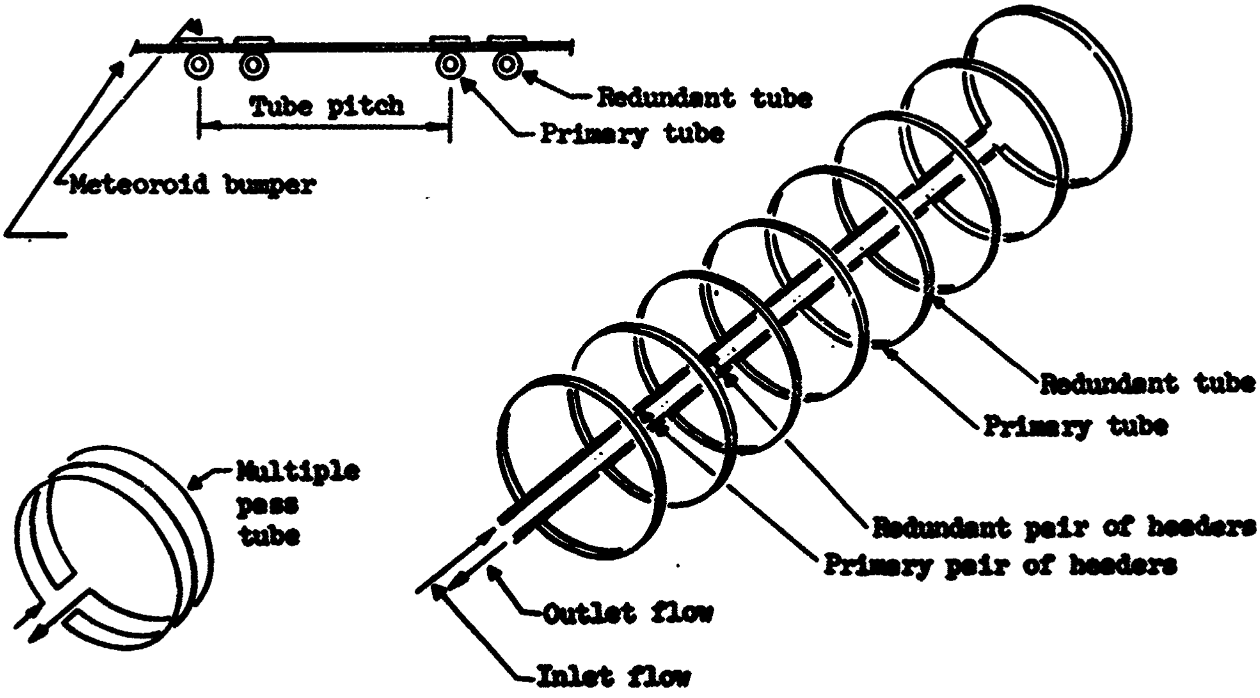


Figure 4-43. Space Radiator Model

itself to the use of an average space sink temperature rather than determining a circumferential sink temperature distribution. Subsequently, this greatly reduces the detailed design computational effort required in sizing the space radiators. A sensitivity analysis was performed as a part of this study to determine for interplanetary flight conditions the effects of assuming an average sink temperature. This assumption may be inherently less valid for these conditions than for orbital conditions because of the absence of any radiative heating to the shadowed side of the vehicle. That is, the circumferential environmental thermal conditions are more nonuniform and include greater temperature differences for interplanetary conditions than for orbital conditions. The results of this sensitivity analysis indicate that radiator sizing computations will be no more than 15% in error over more exact methods through the use of the average sink temperatures for interplanetary flight conditions as are shown in Figure 4-44.

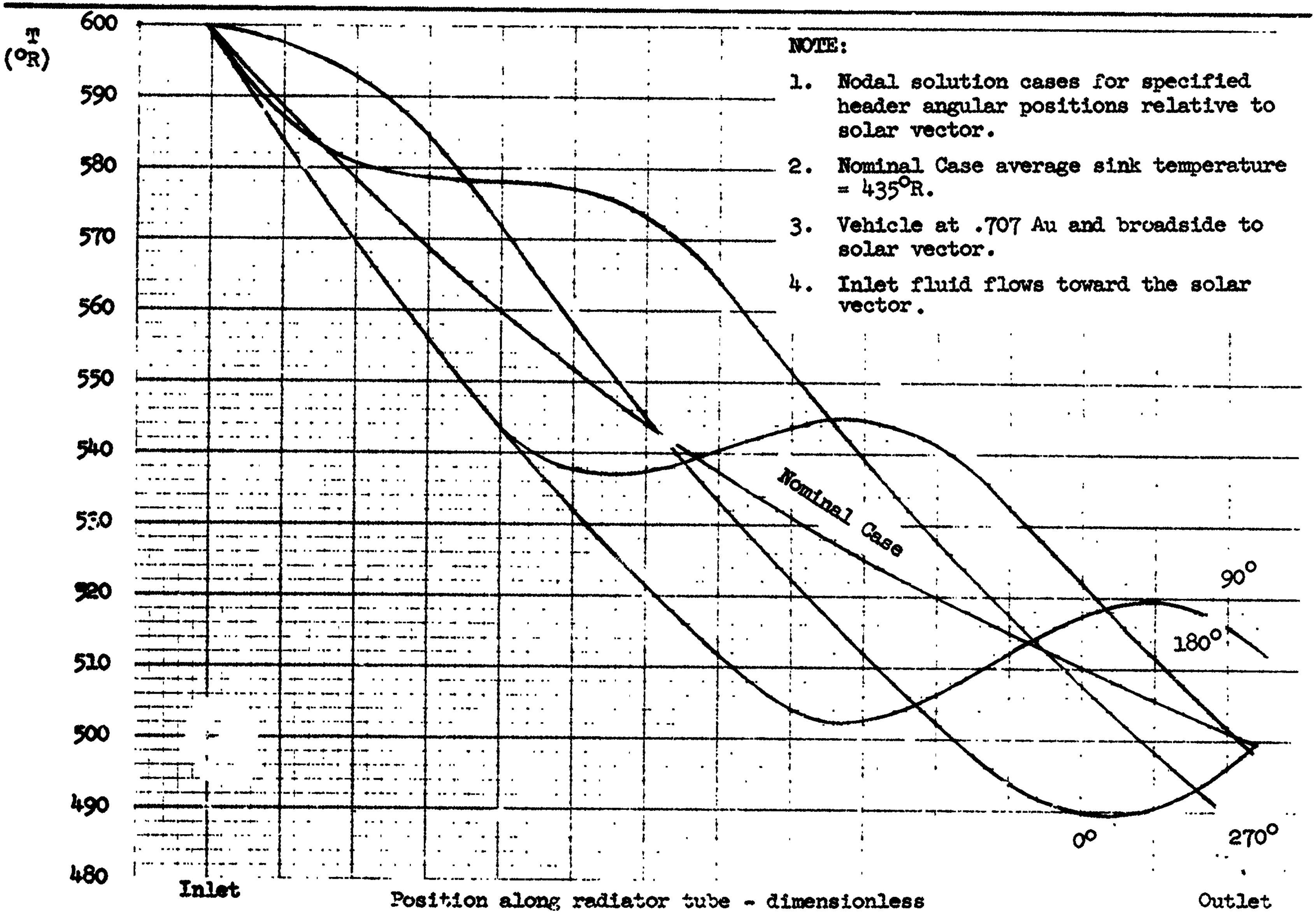
Another consideration involves weight as influenced by radiator tube diameter and the pumping power required to overcome the resistance caused by the fluid flow. In sizing radiators, it has been found necessary to consider the inherent tradeoff between fixed weight and required pumping power. Fixed weight includes the weight of heat transport fluid, tubing, meteoroid shielding, and any required additional structure. The required power is that electrical power supplied to the radiator fluid circulation pump. Later in this section the overall effective radiator weight ($W_{E,R}$) relationship is derived; however, it is given here to show the major input variable:

$$W_{E,R} = \underbrace{K_1 D_t^2}_{\text{fluid}} + \underbrace{K_2 D_t + K_3}_{\substack{\text{tubing,} \\ \text{meteoroid} \\ \text{shielding} \\ \text{and} \\ \text{additional} \\ \text{structure}}} + \underbrace{K_p \frac{K_4}{D_t^4} + K_p \frac{K_5}{D_t^5}}_{\text{electrical power}} \tag{4-62}$$

K_1 to K_5 = Constants based on assumed radiator characteristics

D_t = Tubing diameter, m

K_p = Power penalty factor, kg/kW$_e$



NOTE:

1. Nodal solution cases for specified header angular positions relative to solar vector.
2. Nominal Case average sink temperature = 435°R.
3. Vehicle at .707 Au and broadside to solar vector.
4. Inlet fluid flows toward the solar vector.

Figure 4-44.—Variations in Radiator Fluid Temperature with Circumferential Position

In the above equation, it is assumed that heat transfer relationships have determined the required surface area of the radiator and that this determination has involved the subsidiary determination of the spacing between the parallel radiator tubes. Radiator area and tube spacing then set the number of radiator tubes. The remaining consideration is to determine the tube diameter. It should be noted that Equation 4-62 does not include a weight term for the radiator fin material, that portion of the space radiator utilizing the basic vehicle outer shell as radiator surface area. It is assumed that the weight of this structure is accounted for as part of the vehicle structure. As should be expected, the weight of fluid and tubing increases with increase in the tube diameter and the equivalent weight caused by power decreases with increases in tube diameter. It should be noted that the changes in equivalent power are more sensitive to changes in tube diameter than are the changes in fixed weight. Optimization studies in Reference 4-55 have indicated that the fixed weight terms and equivalent weight due to power terms are of similar importance. Some spacecraft studies have indicated that radiator sizing can be quite critical in that there might not be sufficient available surface area of the outer shell of the vehicle for the space radiator. When this occurs, the required additional surface area can be obtained by adding vehicle length or free-standing radiator panels, but at a significantly greater increment of weight as the weight of the structure involved is now assessed to the life support system. Preliminary and cursory studies for this study have shown that to obviate providing additional radiator structure by spacing the radiator tubes very close together to adequately improve the heat transfer characteristics of the radiating vehicle structure can also bring prohibitive weight increases. Spacing tubes close together requires additional tube and fluid weight. These opposing factors have thus led to the necessity for including the computational logic to determine reasonable estimates for minimal space radiator effective weights.

Transient thermal analyses of space radiator systems with physical configurations of the type considered in this study have demonstrated thermal time constants of the order of fractions of an hour (Reference 4-55). Since, even with transient variations in the thermal environment, the radiator will rather rapidly approach steady state conditions, it is thus appropriate to size the space radiator on the basis of its particular thermal environmental conditions. In most cases, the maximum expected average sink temperature is selected as the basis for this computation. For orbital conditions, this usually occurs at the intersection of the orbital path and the planet-sun line, or the sub-solar point.

The computer program permits various locations around the orbital path to be specified for this calculation, that is, from Figure 3-20: $\beta \leq 90°$ at $\delta = 0$, and $\Omega = 0$ can be specified. For interplanetary flight conditions the combination of heliocentric location and vehicle orientation which provide the highest sink temperature usually are specified.

The foregoing has presented the rationale and the variables to be considered in characterizing the space radiator components. In the titled paragraphs which follow, detailed discussions are given for tube header orientation, sink temperatures and view factors, meteoroid protection, loop configuration, cooling fluid selection, and the procedure for sizing radiators.

Tube Header Orientation

An orbiting vehicle receives direct solar, reflected solar (albedo), and planetary emitted radiant energy during sunlit portions of orbits. These heat sources and this heating environment are detrimental to space radiator performance and thus provide the environmental conditions which are used in designing the space radiator and especially in locating the tube supply and return headers. At the subsolar point direct solar heating is incident on the portion of the vehicle facing the sun and albedo and planetary emitted radiation are incident upon the opposite side of the vehicle, and the effective thermal environment is somewhat distributed around the vehicle circumference. This condition has significantly aided in the validity of an assumed average sink temperature.

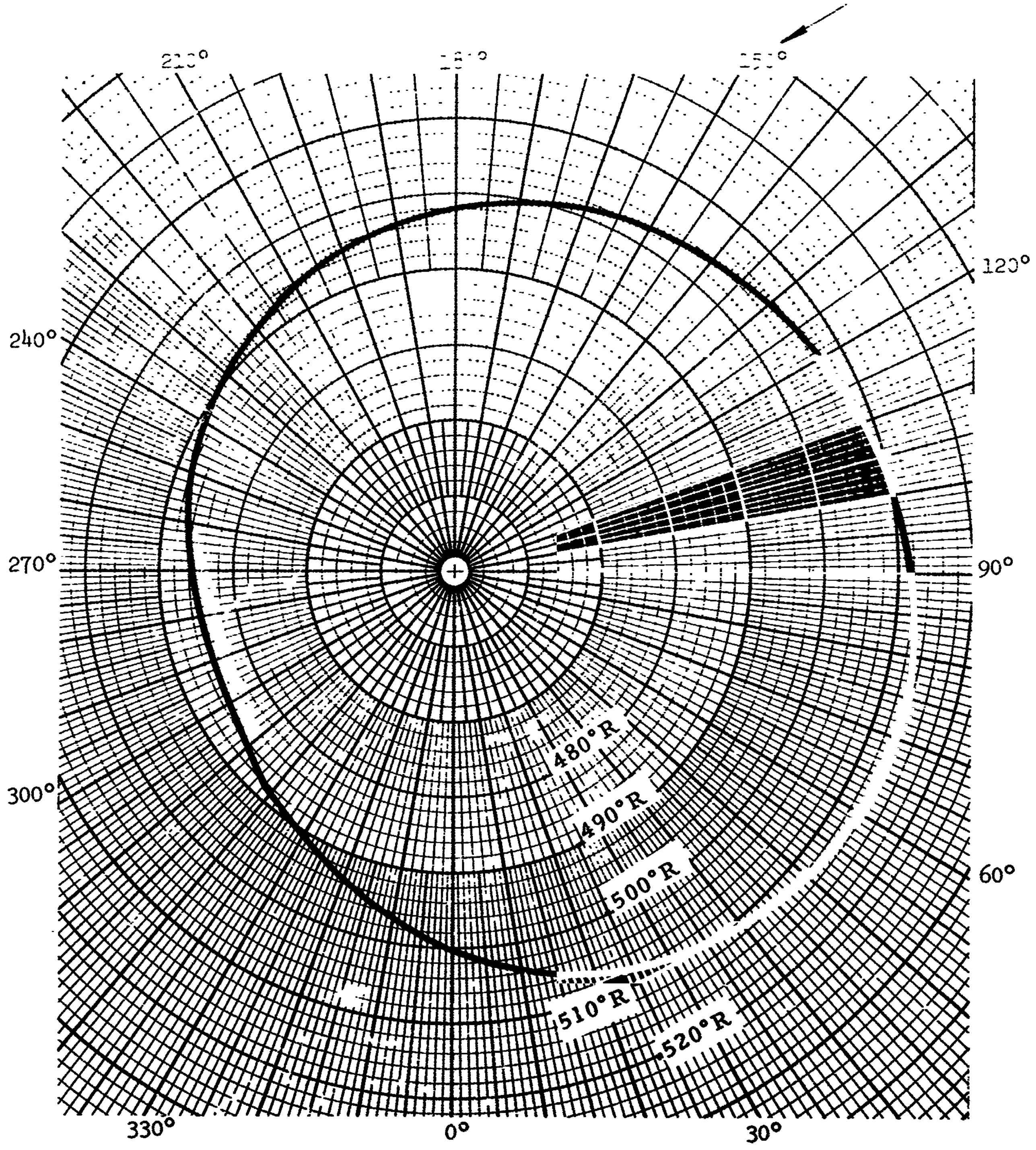
In interplanetary flight, entirely different conditions exist, planetary emitted energy and albedo will be negligible and the vehicle will be heated by the sun on one side while essentially facing deep space on the other. Since this presents a sink temperature distribution consisting of relatively high values on the sun side and close to zero on the opposite side, a sensitivity analysis was performed to evaluate the error between using an assumed average sink temperature and a more exact model. The condition in which a cylindrical vehicle was oriented broadside to the sun was evaluated. A radiator system was determined by the radiator sizing computer program developed for this study and the average sink temperature was used in this computation. For comparison, a parallel multinode thermal model computer program was used. This allows the true sink temperature distribution to be used, and it computes the fluid temperature at each nodal point around the circumference of the vehicle. The position of the inlet and outlet headers was then varied systematically relative to the solar vector.

Figure 4-44 shows the temperature along the radiator tube for adjacent inlet and outlet headers located at 0°, 90°, 180°, and 270° to the solar vector. The temperature distribution for a circumferential and average sink temperature of 435°R is also shown. A flight path heliocentric location of 0.707 AU in conjunction with the broadside orientation was examined. This provides an extreme in nonuniform distribution of local sink temperatures. This flight location should provide near-maximum variation between the two computational methods. It is seen that although the temperature distribution along the tubes varies considerably, the outlet temperature obtained (about 500°R) is almost the same as that obtained by means of computations using the average sink temperature assumption. The circumferential variation in exit temperature is shown in Figure 4-45. The maximum deviations are 15% over design and 13% under design, if the average exit temperature as determined by the average sink temperature solution is used to represent the nominal value. Therefore, it is equally likely that any given time the radiator performance will be slightly above or slightly below nominal.

Sink Temperatures for Space Radiators

The defining equation for sink temperature from Subsection 3.2.2 is as follows:

$$T_s = \left\{ \frac{1}{\sigma} \left[\frac{\alpha_s}{\epsilon_t} S\,F_s + \frac{\alpha_s}{\epsilon_t} SAF_{ar} + \frac{(1-a)}{4} SF_{ir} \right] \right\}^{1/4} \qquad (4\text{-}63)$$



NOTE: Angular coordinate denotes angular position of headers relative to solar vector.

Figure 4-45. Variations in Radiator Fluid Outlet Temperature as Function of Header Location where,

σ = Stefan-Boltzmann constant, 0.59×10^{-10} kW/m^2 °K^4

α_s = absorptivity of space radiator surface, dimensionless

ϵ_t = emissivity of space radiator surface for thermal radiation, dimensionless

S = solar flux, kW/m^2

F_s = view factor for solar radiation, dimensionless

a = planet albedo, dimensionless

F_{sr} = view factor for solar radiation reflected from planet (albedo) dimensionless

F_{ir} = view factor for planet emitted radiation, dimensionless

Solar flux, S, is related to distance from the sun,

$$S = 1.4\,(AU)^{-2}\ kW_t/m^2 \tag{4-64}$$

where,

AU = distance from sun, astronomical units

The value of α_s/ϵ_t may be specified. Currently used estimates for this value are $\alpha_s/\epsilon_t \cong 0.2$

The view factors F_s, F_{sr}, and F_{ir} depend upon vehicle orientation relative to the solar vector and the orbital conditions. The geometric coordinates are δ, Ω, β, and i shown in Figure 3-20.

$$F_s = \frac{1}{\pi}\cos\gamma \tag{4-65}$$

where γ is the angle between the solar vector and a plane normal to the vehicle longitudinal axis. F_{ir} depends upon the ratio of orbital altitude, h, to planet radius, r. Values of F_{sr} for $0 \le \beta \le 90°$, $\delta = 0$, $i = 90°$, $\Omega = 0$ and a range of h/r for a cylinder with line of flight orientation are given in Table 4-30. Values for F_{ir} are also presented in the table. Values of planet

Table 4-30

PLANETARY VIEW FACTORS

		F_{sr}			
h/r	F_{ir}	$\beta = 0$	$\beta = 30°$	$\beta = 60°$	$\beta = 90°$
0.029	0.402	0.401	0.348	0.200	0.0053
0.174	0.27	0.262	0.227	0.131	0.0138
0.29	0.214	0.204	0.177	0.102	0.0148
1.76	0.0431	0.0356	0.0308	0.0185	0.00651
2.9	0.021	0.0164	0.0141	0.0088	0.00351

Note:

1. F_{ir} and F_{sr} data from Reference 4-56.
2. F_{sr} data for $\delta = 0$, $i = 90°$, $\Omega = 0$, see Figure 3-20.

radius, albedo, and heliocentric distance for the various planets in the above table and considered in this study are shown in Table 3-4.

Thus, for orbital flight conditions, flight altitude, β, and α_s/ϵ_t are specified and the data in Tables 4-30 and 3-4 are used in Equation 4-63 to determine the average vehicle sink temperature. Interplanetary conditions require only the direct solar radiation term in Equation 4-63. Equation 4-65 is used in obtaining the solar view factor for all cases by using the identity $\beta = \gamma$.

Meteoroid Protection

The following rationale applies to the reliability of the radiator system with regard to meteoroid flux. The probability of no penetration of each set of radiator tubes is P(0), and it is defined in terms of meteoroid flux, target area, and time; see Subsection 3.2.3. The vehicle areas affected by asteroidal flux, A_a, and cometary flux, A_x, are defined as follows:

$$A_s = N D_v K_b D_t \tag{4-66}$$

$$A_c = N \pi D_v K_b D_t \tag{4-67}$$

where,

N = Number of tubes

D_v = diameter of vehicle (m)

D_t = tube diameter (m)

K_b = meteoroid bumper width factor (dimensionless)

The probability of failure or meteoroid penetration of one set of radiator tubes is $1 - P(0)$. The probability of failure for two sets of tubes is then $[1 - P(0)]^2$, and the probability that this double failure does not occur is $1 - [1 - P(0)]^2$. Thus, the reliability $R(r)$ for the two sets of radiator tubes is:

$$R_r = 1 - [1 - P(0)]^2 \tag{4-68}$$

R_r is considered to be a specified desired quantity. $P(0)$ is then determined from Equation 4-68 using the procedure outlined in Subsection 3.2.3 to obtain the meteoroid bumper thickness for each set of tubes.

Heat Transport Loop Configuration and Fluid Selection

As was indicated earlier an analysis was completed which compared dual-loop cooling circuitry with a single-loop cooling circuit. The dual loop consists of a cooling loop which interfaces with the components to be cooled and a radiator loop which rejects this heat to space. These two loops are thermally connected through an interface heat exchanger. Water was selected for the fluid to be used in the cooling loop, since this loop would be located entirely within occupied cabins and because of its good heat transport properties, no exposure to environmental freezing temperatures, lack of toxicity problems, lack of corrosiveness, lack of flammability problems, and adaptability to storage, handling, and maintenance procedures. Freon 21 has been selected for use in the radiator loop because of its good heat transport properties and low freezing temperature. Heat transport fluid properties for other potential fluids are given in Reference 4-57. A Freon was similarly selected for the radiator fluid in this reference. Toxicity, handling characteristics, and other characteristics important when proximity to crewmen is involved are not so important in the selection of the fluid for the radiator loop as it is located entirely outside the vehicle pressure shell.

The single-loop cooling circuit interfaces with both the liquid-cooled components and the space radiator. The fluid selected for this cooling circuit was FC-75. This fluid satisfactorily meets the heat transport and crew proximity requirements listed above for the cooling loop; however, the freezing temperature for this fluid is intermediate between that for water-glycol mixtures (used for radiator fluid on Gemini and Apollo spacecraft) and Freon 21. FC-75 was selected as the heat transport fluid for the MORL single-loop cooling circuit on the basis of superior single-loop properties and good heat transport characteristics (Reference 4-49).

The sensitivity analysis to compare the single and dual loop type circuits consisted of specifying representative manned vehicle radiator requirements and determining the radiator effective weights using either FC-75 or Freon 21 as radiator fluids and either high or low values for the electrical power penalty. The sample problem conditions are given in Table 4-31. Allowances for the dual-loop interface heat exchanger weight, difference in radiator supply plumbing weight, and the pumping requirements for the two cases are included in the comparisons. The numerical comparisons presented were obtained for a mathematical model which included only radiator tubes, fluid, radiator tube pressure drop, and meteoroid protection bumpers.

The radiator effective weights are plotted in Figure 4-46 and 4-47 for a range of radiator areas and for a high and a low electrical power penalty, respectively. The radiator data points shown in Figures 4-46 and 4-47 are for particular optimum design conditions and include both single and dual

Table 4-31

SAMPLE RADIATOR PROBLEMS FOR SENSITIVITY ANALYSIS

	English Units	Metric Units
Rejected heat	50,000 Btu/hr	14.600 kW_t
Inlet temperature	575°R	320°K
Outlet temperature	495°R	275°K
Freon flow rate	2404 lb/hr	1095 kg/hr
FC-75 flow rate	2561 lb/hr	1165 kg/hr
Vehicle diameter	30 ft	9.15 m
Vehicle outer shell thickness-radiator fin	0.020 in.	0.051 cm
Radiator tube thickness	0.1 in.	0.25 cm
Radiator surface emissivity	0.925	0.925
Environmental sink temperature	430°R	240°K
Power penalty factors	1 lb/watt	0.45 $kg/watt_e$
	0.1 lb/watt	0.045 $kg/watt_e$
Range of available radiator area	750 ft^2 to 1400 ft^2	70 m^2 to 130.0 m^2

loop radiators. Computed values for Reynolds numbers, tube passes, tube diameter, tube pitch, and radiator fin effectiveness are indicated on the figures. The solutions were obtained by using the radiator sizing procedure detailed later in this section. For each specified radiator area plotted, the effective weight is the minimum value of all those obtained for the case. Reynolds number is assumed to be 10,000 or higher to insure turbulent flow heat transfer characteristics.

For dual-loop circuits, the effective weights of plumbing are less than those for single-loop circuits. This occurs because with equal lengths of tubing and equal heat transfer requirements water circuits are lighter and require

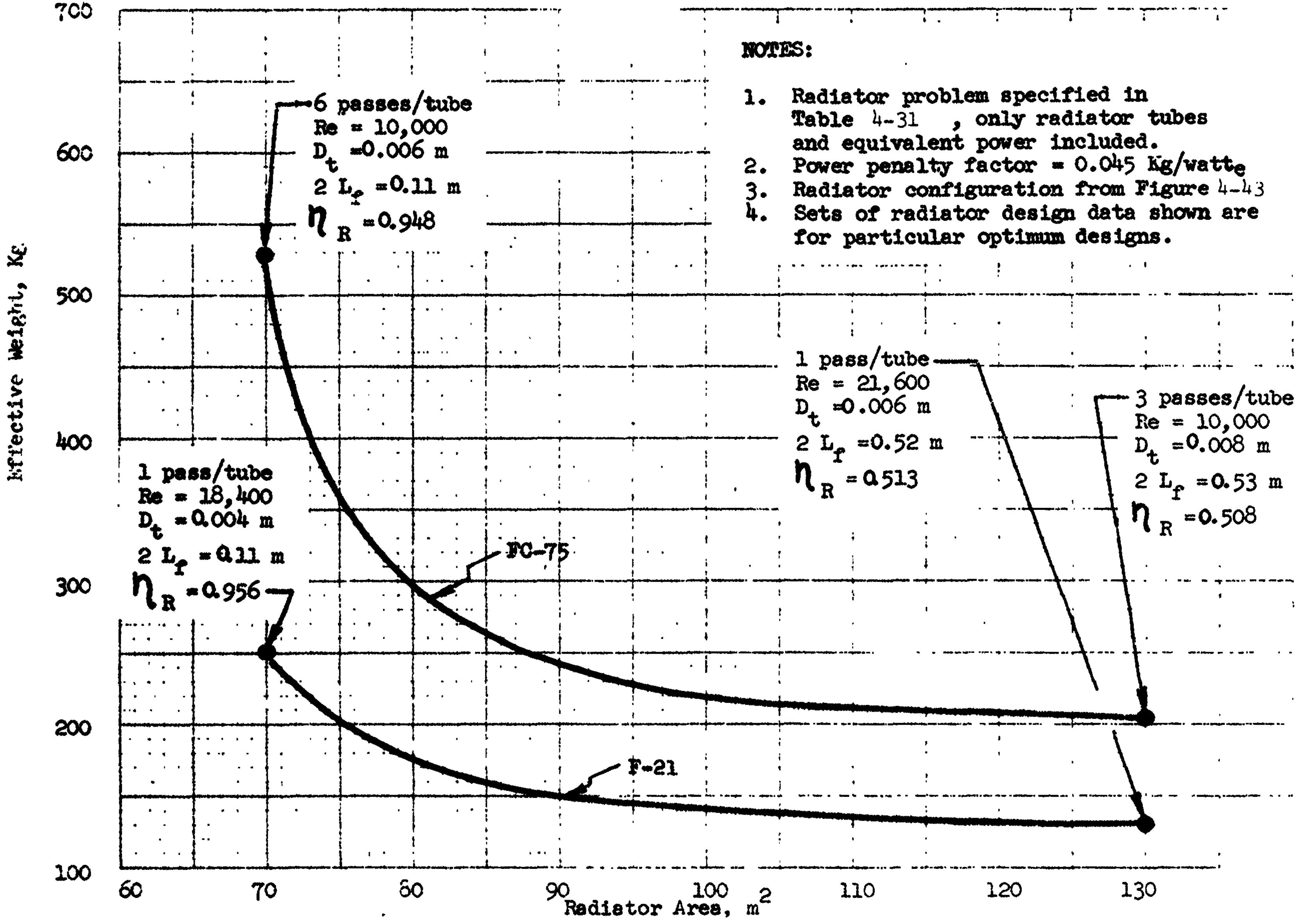
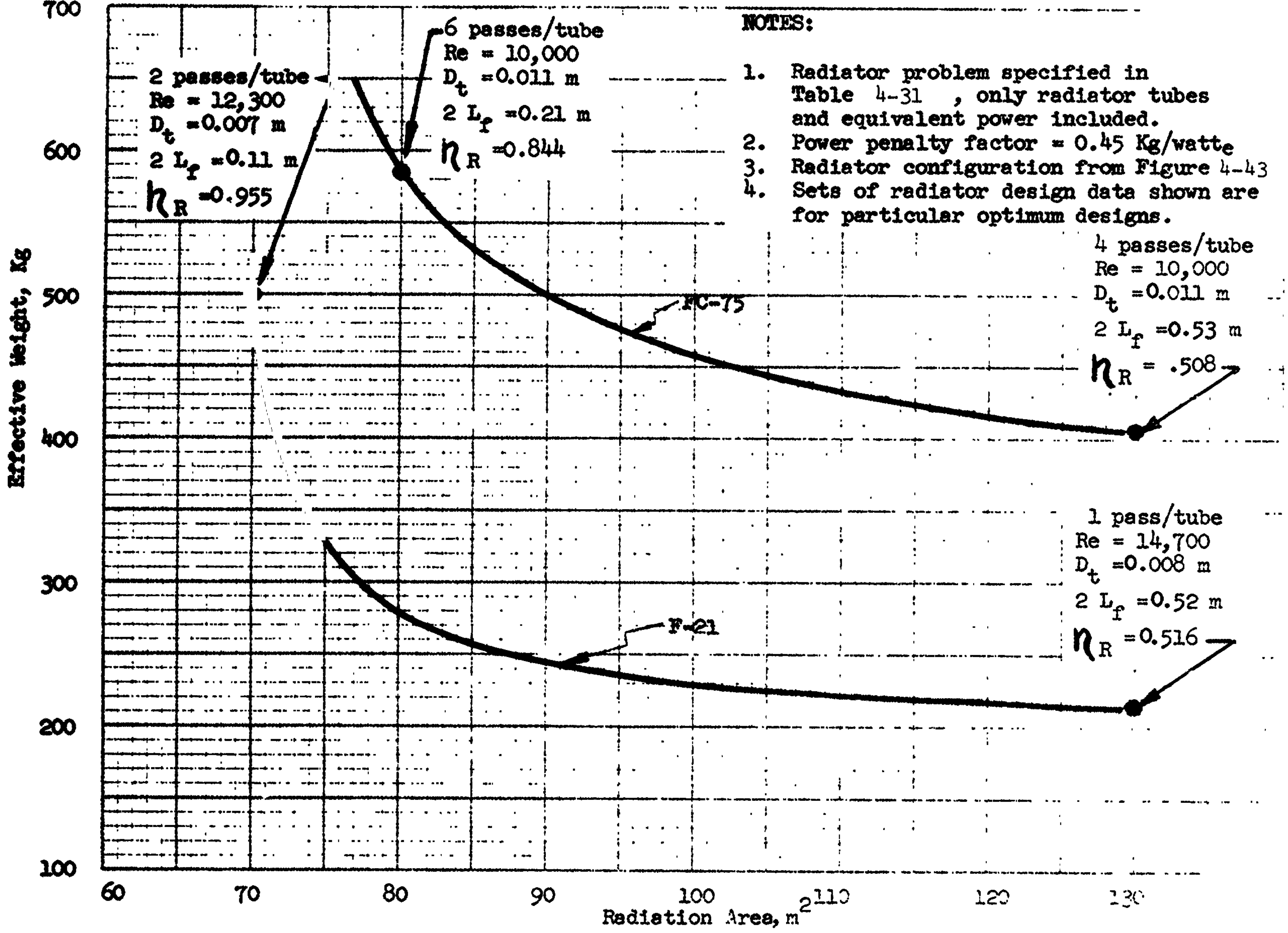


Figure 4-46. Effective Radiator Weight – Low Power Penalty Factor



NOTES:

1. Radiator problem specified in Table 4-31 , only radiator tubes and equivalent power included.
2. Power penalty factor = 0.45 Kg/$watt_e$
3. Radiator configuration from Figure 4-43
4. Sets of radiator design data shown are for particular optimum designs.

Figure 4-47. Effective Radiator Weight — High Power Penalty Factor less power than FC-75 circuits (Reference 4-57). Briefly, water is generally a superior heat transport fluid because of its properties of high specific heat, low density, low viscosity, and high thermal conductivity. Thus that portion of the circuit which uses water in the dual-loop case has a smaller effective weight than that for the corresponding portion of single-loop circuit which uses FC-75. The incremental effective weight for the interface heat exchanger required by the dual-loop circuit is about 34 kg for a power penalty factor of 0.45 kg/watt$_e$, Reference 4-55.

Considering the influences of both the interface heat exchanger, the plumbing, and electrical power, it is seen that the differences in additional effective weights, which are added to the data in Figures 4-46 and 4-47 to obtain dual circuit effective weights, are less than 34 kg. But, the dual-loop effective weights in Figures 4-46 and 4-47 are at least 80 kg less than those for the single-loop cases. The total effective weights for the dual loop circuits therefore, are always less than those for the single-loop circuits. Based on this detailed sensitivity analysis the dual loop circuitry was selected for the program logic, and no provision for the single loop was included.

Procedure for Sizing Space Radiators

The maximum available total cabin external surface area, A_R, which can provide radiator surface area must be specified in radiator sizing computations. This area is determined from the specified cabin volumes, vehicle diameter, and percentage of surface area which may be used as the life support system space radiator. The condition for the interface heat exchanger is assumed to be a temperature difference of 2.8°K (5°R) between the interface heat exchanger cooling loop inlet temperature and radiator loop outlet temperature. The Freon 21 flow rate and radiator inlet temperature are determined from the heat transferred to the radiator fluid.

The steady state equation relating decrease in enthalpy of the radiator fluid to heat transferred from the radiator surface area as derived in Reference 4-58 is as follows:

$$\dot{q}_R = \dot{w} C (T_i - T_o) \qquad (4\text{-}69)$$

$$\dot{q}_R = \frac{\sigma \epsilon A_R \eta_R T_s^3 (T_i - T_o)}{\zeta(\tau_2) - \zeta(\tau_1)} \qquad (4\text{-}70)$$

T_i = Fluid inlet temperature, °K

T_o = Fluid outlet temperature, °K

$\dot{q}_R$ = Heat transferred from radiator, kW

$\dot{w}$ = Coolant flow rate, kg/hr

C = Coolant specific heat, kW-hr/kg°K

$T_{R,i}$ = Radiator fin root temperature at fluid inlet, °K

$T_{R,o}$ = Radiator fin root temperature at fluid outlet, °K

T_s = Sink temperature, °K

σ = Stefan-Boltzmann constant, 0.59×10^{-10} kW/m^2 °K^4

ϵ = Surface emissivity, dimensionless

η_R = Radiator fin effectiveness, dimensionless

A_R = Radiator surface area. m^2

and

$$\tau_2 = \frac{T_{R,o}}{T_s}$$

$$\tau_1 = \frac{T_{R,i}}{T_s}$$

$$\zeta(\tau) = \frac{1}{4} \ln \left[\frac{\tau + 1}{\tau - 1}\right] + \frac{1}{2} \tan^{-1} \tau$$

The heat transferred from the radiator, q_R, can also be expressed in the following form:

$$\dot{q}_R = \sigma \epsilon A_R \eta_R \left(T_{R,e}^4 - T_s^4\right) \qquad (4\text{-}71)$$

where

$T_{R,e}$ = Effective fin root temperature for the radiator surface, °K

By combining Equations 4-70 and 4-71, $T_{R,e}$ is,

$$T_{R,e} = \left[\frac{T_s^3 (T_i - T_o)}{\zeta(\tau_2) - \zeta(\tau_1)} + T_s^4 \right]^{\frac{1}{4}} \qquad (4\text{-}72)$$

An initial estimate for $T_{R,e}$ may be obtained from Equation 4-72 by assuming that the inlet and outlet fin root temperatures are equal, respectively, to the inlet and outlet fluid temperatures, and Equation 4-71 can be solved for the fin effectiveness, η_R, and the quantity is then used to determine the assumed corresponding fin half width, L_f. If the computed value of η_R is greater than 0.97 then it is indicated that insufficient area has been specified for the space radiator. In this event, either (1) additional structure must be added to the vehicle to provide space radiator area or (2) a water evaporator must be added to the system to supplement the heat rejection capabilities of the specified space radiator. If the first type is assumed, the effectiveness is set equal to 0.97 and the required additional area, ΔA_R, is computed. This area would be added as a skirt extension to the cylindrical shell of the vehicle without changing the cabin volumes. For the second type, the allocated area is used for the space radiator and the radiator outlet temperature is increased to a value which is consistent with a radiator fin effectiveness of 0.97. An iterative procedure is necessary to determine the outlet temperature corresponding to $\eta_R = 0.97$, and as can be seen in Figure 4-40 the cooling loop interface heat exchanger water outlet temperature is correspondingly increased when the radiator outlet temperature is increased. The water evaporator would then be inserted in the cooling loop and it is sized to reduce the cooling loop temperature to the required or specified cooling loop temperature level. The fin half width, L_f, corresponds to half the tube pitch indicated on Figure 4-43. Relationships between η_R and L_f have been determined in Reference 4-59. Numerical solutions have been plotted in the reference and there is a very weak influence shown for the ratio, T_s/T_R. If the value for $T_s/T_R = 1$ is assumed, and it appears to be sufficiently accurate for this study, the relationship then is,

$$\eta_R = \frac{\tanh 2L_f\sqrt{\sigma\epsilon T_{R,e}^3/k_f\Delta_f}}{2L_f\sqrt{\sigma\epsilon T_{R,e}^3/k_f\Delta_f}} \tag{4-73}$$

where,

k_f = Thermal conductivity of the fin material, kW/m °K

Δ_f = Fin thickness, m

At this stage of the life support system computational logic, the fin thickness, or vehicle outer shell thickness has been assumed or determined by the requirements for meteoroid protection. L_f (and consequently the tube spacing) is determined by a trial and error solution of Equation 4-73.

At this stage, the temperature drop across the liquid film between the fluid bulk flow and the tube wall has been ignored. This means that the computed value for $T_{R,e}$ is too high because there is an actual temperature drop and a correction in $T_{R,e}$ for this effect must be determined as in the following procedure.

Other space radiator studies have indicated the advantages of assuming turbulent fluid flow rather than laminar flow in the space radiator tubes (Reference 4-49). Net savings in effective weight of space radiator systems have been achieved through this selection of flow regime. For assumed turbulent fluid flow, the heat transfer across the tube wall is,

$$\dot{q}_R = h_c A_t \Delta T_{film} \tag{4-74}$$

and h_c is determined from

$$h_c = 0.023\frac{k_\ell}{D_t}Re^{0.8}Pr^{0.4} \tag{4-75}$$

where

h_c = Convective film heat transfer coefficient, kW/m^2 °K

A_t = Tube wall heat transfer area, m^2

ΔT_{film} = Temperature drop across fluid film °K

k_ℓ = Thermal conductivity of fluid, kW/m °K

D_t = Tube diameter, m

Re = Reynolds number, dimensionless

$$Re = \frac{\dot{w}}{900\pi\mu N_t D_t} \geq 10,000 \text{ to insure turbulent flow} \tag{4-76a}$$

Pr = Prandtl number, dimensionless

$$Pr = \frac{\mu c}{k_\ell} \tag{4-76b}$$

N_t = Number of parallel radiator tubes

μ = Fluid viscosity, kg/m sec.

The number of parallel radiator tubes N_t is determined from the length of the cylindrical radiator L_R and the tube spacing $2L_f$. If the volume of each cabin, $V_c(i)$, is given, then:

$$V_c(i) = \frac{\pi D_v^2}{4} L(i) \tag{4-77}$$

where,

D_v = Vehicle diameter, m

L(i) = Cabin length, m

Equation 4-77 may be solved for cabin length L(i) and surface area of cabin i, $A_c(i)$ from Equation 4-78

$$A_c(i) = \pi D_v L(i) \tag{4-78}$$

Total available radiator area is,

$$A_R = \sum_{i=1} A_c(i) \, AF(i)$$

where,

$AF(i)$ = Percentage of surface area of cabin i specified available for use as space radiator, dimensionless

The radiator tubes may be assumed to make one or more passes around the vehicle circumference. Each pass is designated as N_p.

N_p = 1 for the initial sizing computations.

and the number of radiator tubes, N_t, is related to the available radiator area through the following equations;

$$N_p N_t 2 L_f \pi D_v = A_R \tag{4-79}$$

N_t is computed from Equation 4-79 and this value for N_t and an initial estimate for D_t are inserted in Equation 4-76a to obtain an initial value for Re, and to check for turbulent flow, $Re > 10,000$. The film temperature drop ΔT_{film} is then computed from Equation 4-75. This quantity is used to revise the effective fin root temperature $T_{R,e}$, since the initial estimate for $T_{R,e}$ ignored the temperature drop across the fluid film. The revised value for effective film root temperature is designated as $T_{R,e}'$.

$$T_{R,e}' = T_{R,e} - \Delta T_{film} \tag{4-80}$$

$T_{R,e}'$ is used in lieu of $T_{R,e}$ in Equation 4-73 to obtain a revised estimate of η_R. An iterative loop relating T_R, L_f, D_t, h_c, ΔT_{film}, and $T_{R,e}'$ has thus been formulated. The sequence of computations, starting with Equation 4-80, requires Equations 4-80, 4-71, 4-73, 4-79, 4-76a, 4-75 and 4-74, in order, and the return to Equation 4-80 to check for computational convergence.

The weight of the fluid, W_ℓ, and tubing, W_t, for two sets of tubes, are as follows,

$$W_\ell = 2N_t \rho_\ell \frac{\pi}{4} D_t^2 L_t \tag{4-81}$$

$$W_t = 2N_t \rho_m \frac{\pi}{4} L_t \left[(D_t + 2\Delta_t)^2 - D_t^2\right] \tag{4-82}$$

$$= 2N_t \rho_m \pi L_t \left[D_t \Delta_t + \Delta_t^2\right] \tag{4-82a}$$

where,

ρ_ℓ = Density of fluid, kg/m^3

ρ_m = Density of tubing and shield, kg/m^3

Δ_t = Tube wall thickness, m

The weight of the meteoroid shielding is:

$$W_s = 2N_t L_f K_b D_t \Delta_s \rho_m \tag{4-83}$$

where,

K_b = Meteoroid bumper width factor, dimensionless

Δ_s = Meteoroid bumper thickness, m

The weight of any additional structural shell added to the vehicle for use as space radiator surface is

$$W_{as} = \Delta A_R \rho_{as} \tag{4-84}$$

where

ρ_{as} = Weight per unit area of additional structure, kg/m^2

The pressure drop and associated pumping power for the space radiator may now be computed. The pressure drop for each radiator tube is

$$\Delta P_R = \Delta P_L + \Delta P_E$$

where ΔP_L is the pressure drop due to tube wall friction and ΔP_E is the pressure drop due to entrance, exit, and bend effects.

$$\Delta P_L = \frac{fL_t}{D_t}\frac{1}{2g_c}\rho_\ell\ V^2 \tag{4-85}$$

$$\Delta P_E = 2(1 + N_b)\frac{1}{2g_c}\rho_\ell\ V^2 \tag{4-86}$$

where,

f = Friction factor, dimensionless

$$f = \frac{0.316}{Re^{0.25}} \text{ for turbulent flow} \tag{4-87}$$

L_t = Tube length, m

$$L_t = \pi D_v N_p \tag{4-88}$$

g_c = Proportionality factor in Newton's second law $\frac{m}{hr^2}\frac{kg_m}{kg_f}$

ρ_ℓ = Fluid density, kg/m^3

V = Fluid velocity, m/hr

$$V = \frac{\dot{w}}{\rho_f \frac{\pi}{4} D_t^2 N_t} \tag{4-89}$$

N_b = Number of bends = $N_p - 1$

Substituting Equations 4-87, 4-88, and 4-89 into Equation 4-85 and Equation 4-89 into Equation 4-86,

$$\Delta P_L = 3.20 \frac{D_v N_p \dot{w}^2}{Re^{0.25} g_c \rho_\ell N_t^2} \frac{1}{D_t^5} \tag{4-90}$$

$$\Delta P_E = 1.62 \frac{N_p \dot{w}^2}{g_c \rho_\ell N_t^2} \frac{1}{D_t^4} \tag{4-91}$$

and the pumping power P is,

$$P = \frac{\dot{w} \Delta P_R}{\rho_\ell \eta_p} \left(2.72 \times 10^{-6} \frac{\text{kW hr}}{\text{m kg}}\right), \text{ kW}_e \tag{4-92}$$

where

η_p = Overall pump efficiency, dimensionless

The equivalent weight due to the pumping power is,

$$W_p = K_p P \tag{4-93}$$

where

k_p = Power penalty factor, kg/kW$_e$

Combining Equations 4-90, 4-91, 4-92, and 4-93

$$W_p = 8.7 \times 10^{-6} \frac{D_v N_p \dot{w}^3 K_p}{Re^{0.25} g_c \rho_\ell^2 N_t^2 \eta_p} \frac{1}{D_t^5}$$

$$+ 4.4 \times 10^{-6} \frac{N_p \dot{w}^3 K_p}{g_c \rho_\ell^2 N_t^2 \eta_p} \frac{1}{D_t^4} \qquad (4\text{-}94)$$

The total effective weight for the space radiator $W_{E,R}$ is obtained by summing Equations 4-81, 4-82a, 4-83, 4-84, and 4-94:

$$W_{E,R} = K_1 D_t^2 + K_2 D_t + K_3 + K_p \frac{K_4}{D_t^4} + K_p \frac{K_5}{D_t^5} \qquad (4\text{-}62)$$

where,

$$K_1 = 2N_t \rho_\ell \frac{\pi}{4} L_t \qquad (4\text{-}95a)$$

$$K_2 = 2N_t \rho_m \pi L_t \Delta_t + 2N_t L_f K_b \Delta_s \rho_m \qquad (4\text{-}95b)$$

$$K_3 = 2N_t \rho_m \pi L_t \Delta_t^2 + \Delta A_R \rho_{as} \qquad 95c)$$

$$K_4 = 4.4 \times 10^{-6} \frac{N_p \dot{w}^3}{g_c \rho_\ell^2 N_t^2 \eta_p} \qquad (4\text{-}95d)$$

$$K_5 = 8.7 \times 10^{-6} \frac{D_v N_p \dot{w}^3}{Re^{0.2} g_c \rho_\ell^2 N_t^2 \eta_p} \qquad (4\text{-}95e)$$

As indicated, the effective weight is initially determined for the tube diameter corresponding to Re $\geq$10, 000. Once this value is obtained, the procedure is repeated for an incremental increase in the tube diameter. This second value for effective weight is compared with the first value for a possible reduction in effective weight. Depending on the outcome of this computation, and comparison with the first weight, a third trial calculation may be needed using a second incremental change in tube diameter. If decreasing effective weights are achieved with corresponding decreases in Reynolds number in the vicinity of Re = 10, 000 and the minimum is not achieved with Re $\approx$ 10, 000, the number of tube passes N_p is increased by one and the process is repeated. This iteration procedure is repeated until the minimum effective weight is found and the corresponding tube diameter, radiator weight, and power are determined.

To aid in the foregoing computations, some fundamental radiator sizing data are presented in Figure 4-48 and 4-49. Sink temperatures determined from Equations 4-63 and 4-65 are shown in Figure 4-48. These values are for interplanetary conditions and do not include the effects of albedo and planet emitted radiation. Typical earth orbital sink temperatures with Ω = 0 and these effects are in the vicinity of 245°K (440°R). The α_s/ϵ_t value of 0.2 used is representative. Radiator areas per thermal kilowatt of unit heat rejected are shown in Figure 4-49 for the nominal radiator outlet temperature of 275°K (495°R), a value for α_s/ϵ_t = 0.2, and a radiator fin effectiveness, η_r, of 1.0. The data shown were determined from Equation 4-70 by using the simplifying assumption that fluid temperatures are equal to corresponding fin root temperatures. Figures 4-46 and 4-47 indicate that "lighter" radiators often result from a locating larger areas than those indicated on Figure 4-49 even though the fin effectiveness is reduced significantly below 1.0. This cursory comparison indicates that rather complete studies involving available area and required pumping power and using radiator sizing procedures such as that outlined in this study should be required in determining optimum radiator weights or sizes.

4.3.3.2 Water Evaporators

Water evaporators are optionally provided in cooling loops to supplement area limited space radiators in accommodating the design heat loads. This

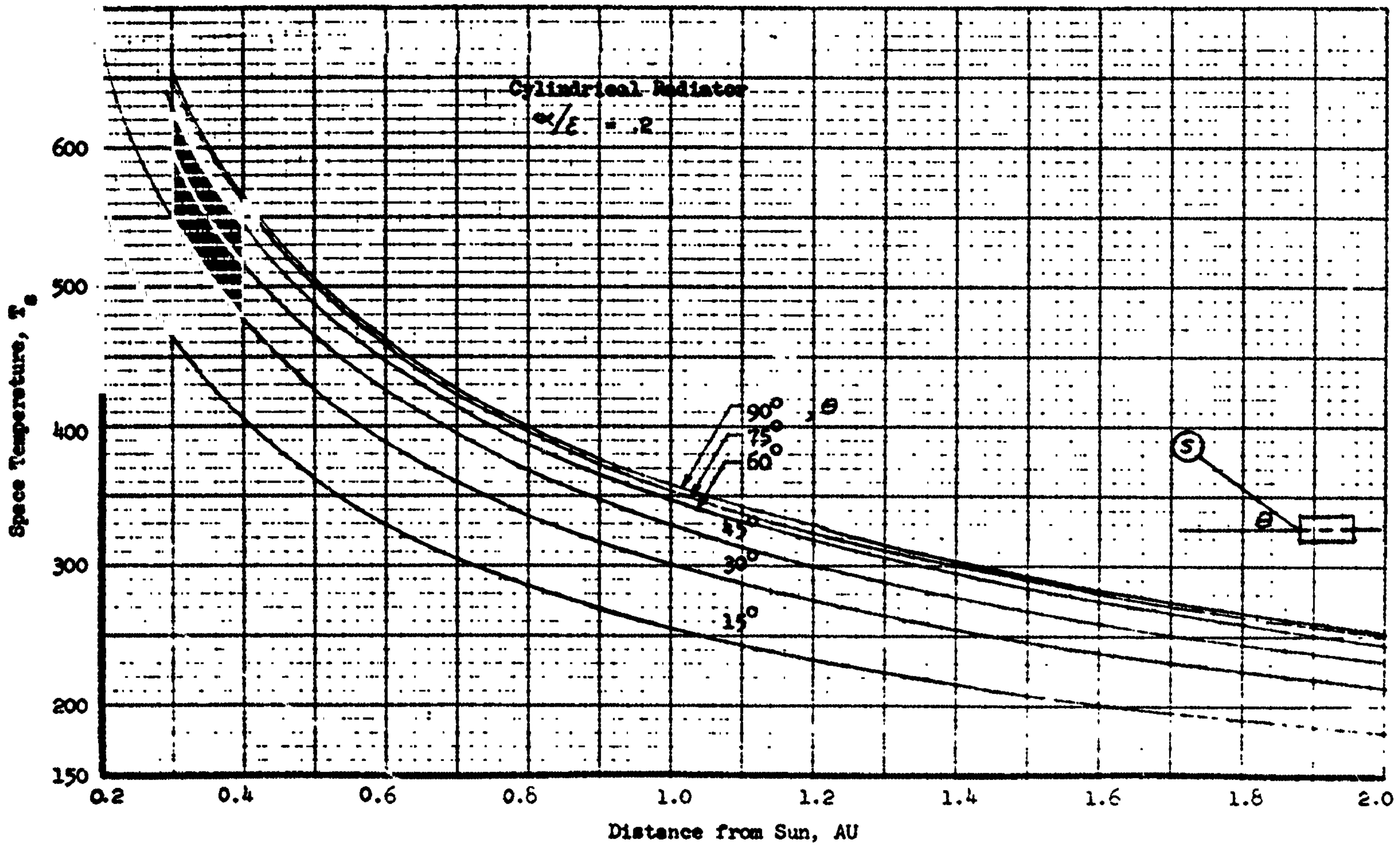


Figure 4-48. Sink Temperature vs Distance from Sun

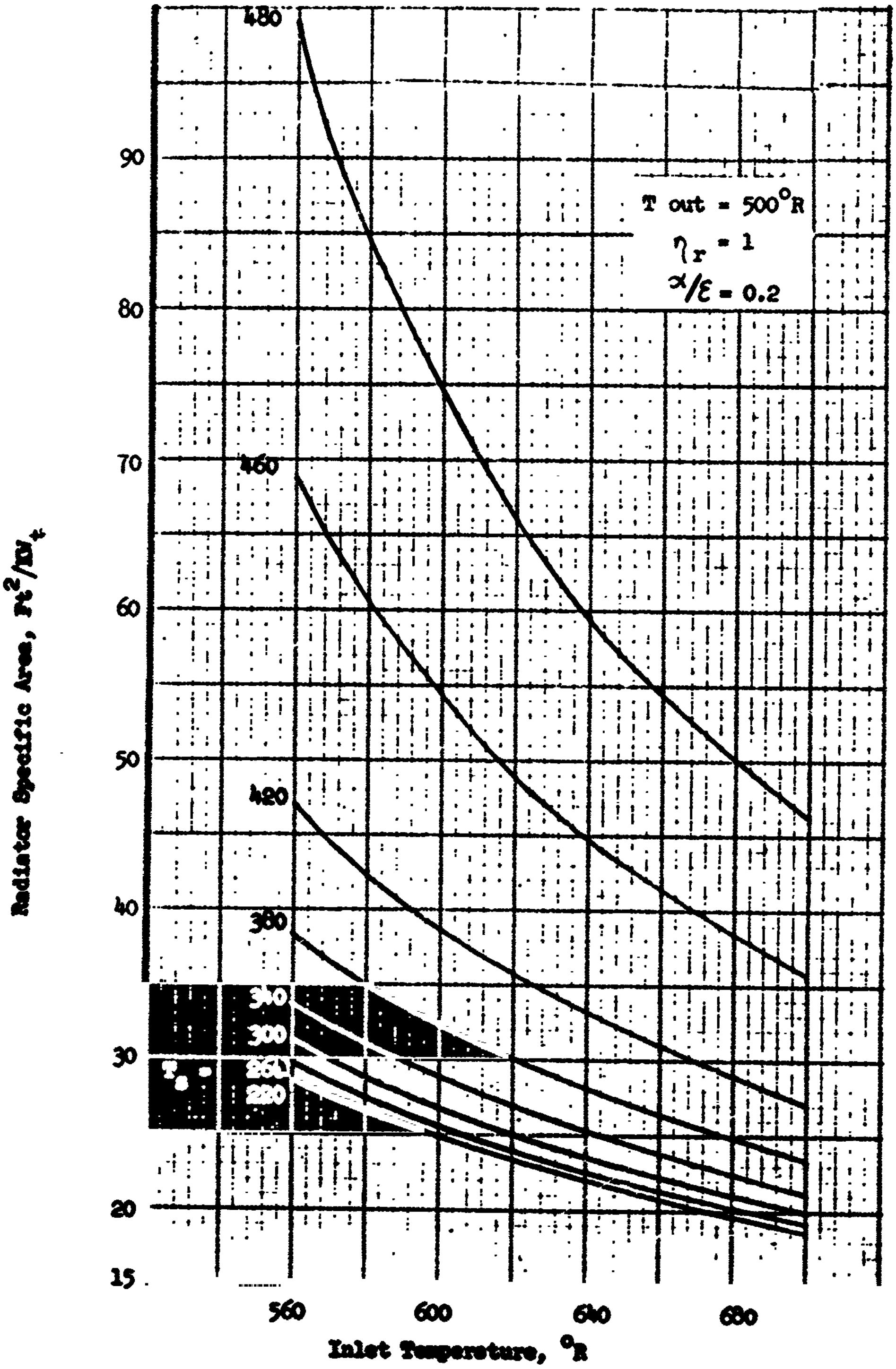


Figure 4-48. Specific Area vs Inlet Temperature

water separator is separate from the water evaporator provided for use in the event of failure of the liquid cooling loop and/or the radiator loop. Data from several water evaporators and sublimators were available for developing scaling laws. These data were plotted as cooling load versus weight and trend lines were established. Similarly, water evaporator volume was plotted versus cooling load.

The resulting equations from these plots are given below:

$$WT = 2.46\ Q,\ \text{kg} \tag{4-96}$$

$$V = 2.8 \times 10^{-3}\ Q,\ \text{m}^3 \tag{4-97}$$

where

WT - weight of water evaporator, kg

V - volume of water evaporator, m^3

Q - heat rejection rate, kW

4.3.3.3 Cold Plates

Scaling laws for cold plate pressure drop, area, and weight are based largely on vendor data from AVCO Corporation (Reference 4-60) and supplemented by scaling data from Reference 4-61. The cold plate construction was assumed to consist of staggered flat plate fins brazed to aluminum sheets (similar to AVCO Corporation type II cold plate). The physical characteristics of the cold plates in terms of its heat load, including fittings and mountings, and assuming a temperature rise of 5.5°K for a given area.

$$\Delta P = 0.068\ Q^{1.39} \tag{4-98}$$

$$W = 3.03\ Q \tag{4-99}$$

$$A = 8.25\ Q \tag{4-100}$$

ΔP = pressure drop of cold plate, kg/cm^2

W = weight of cold plate, kg

A = area of cold plate, m^2

Q = heat load, kW

4.3.3.4 Interface Heat Exchanger

This heat exchanger provides the thermal interface between the cooling loop and the radiator loop. The MDAC-WD H723 heat exchanger program was used to size a typical interface heat exchangers appropriate to this type of application in this study. Scaling laws for these units have been developed from the computed data for the typical heat exchanger. This H723 program is the same as was used for the cabin heat exchanger (Subsection 4.3.2.1), but these heat exchangers are considerably different.

The following representative assumptions of currently planned counterflow interface heat exchangers were used in characterizing a reference heat exchanger.

1. Counterflow plate and fin configuration
2. Core matrix designated as 1/8-19/82 (D) (Reference 4-62) used on both sides. The core was modified from a double fin set to a single fin set with the following characteristics:

Fins per Inch	Plate Spacing (in.)	Offset (in.)	Fin Thickness (in.)	Material
20	0.099	0.125	0.004	Stainless steel

3. Water outlet temperature = 278°K (40°F)
4. Freon inlet temperature = 275°K (35°F)
5. Temperature difference between water inlet and Freon outlet = 3.88°K (7°F)
6. The ratio of total heat exchanger weight to core weight = 1.3:1.0

The additional input data for the reference heat exchanger and the computed results are:

1. Heat load = 14.7 kW_t (50,000 Btu/hr) Input
2. Water inlet temperature = 316°K (110°F) Input
3. Core density (wet), ρ_{HX} = 3,300 kg/m^3 Input
4. Viscosity of water = $9.45 \times 10^{-4} \frac{kg}{m\ sec}$ Input
5. Viscosity of freon = $2.9 \times 10^{-4} \frac{kg}{m\ sec}$ Input
6. Heat exchanger weight (wet) = 30.4 kg Output
7. Core volume = 0.0071 m^3 (0.24 ft^3) Output
8. $\dot{w}_{H_2O}$ = 324 kg/hr (715 lb/hr) Output
9. ΔP_{H_2O} = 0.0099 kg/cm^2 (0.14 psi) Output
10. Re_{H_2O} = 72.4 Output
11. $\dot{w}_{freon}$ = 1360 kg/hr (3,000 lb/hr) Output
12. ΔP_{freon} = 0.033 kg/cm^2 (0.47 psi) Output
13.. Re_{freon} = 873 Output
14. Face area = 0.0048 m^2 (7.4 $in.^2$) Output
15. Flow area/Face area = 0.88 Output
16. Length = 1.48 m (58.5 in.) Output

Heat transfer across counterflow heat exchangers is given by,

$$\dot{q} = UA\,\Delta T_{log\ mean} \tag{4-101}$$

or,

$$\dot{q} = UA \frac{(T_{i,h} - T_{o,c}) - (T_{o,h} - T_{i,c})}{\ln \frac{(T_{i,h} - T_{o,c})}{(T_{o,h} - T_{i,c})}} \tag{4-101a}$$

where the subscripts denote inlet and outlets and hot and cold circuits.

Since these temperature differences were assumed constant, heat transfer is linearly proportional to UA, and UA is related to heat transfer characteristics on each side of the heat exchanger. It has been assumed that the Reynolds numbers were maintained at the reference values, and constant Reynolds numbers insure constant film coefficient, h, and fin effectiveness, η_f. Thus, from Equation 4-37, UA is proportional to the heat transfer area on each side of the heat exchanger and since these areas are equal UA is linearly related to total heat transfer area. Total heat transfer area is linearly related to the product of face area and heat exchanger length. Heat transfer is thus proportional to heat exchanger volume.

The constant Reynolds number assumption means that any change in the value of the face area from that given for the reference case would be in accordance with Equation 4-35 and,

$$\mathrm{Re} = \frac{G\, D_n}{3600\mu} = \frac{\dot{w}\, D_h}{3600\,(A_f/2)\,(A_c/A_f)\mu}$$

where

A_f = Face area, m^2

A_c = Flow area, m^2

For the reference configuration and with the same matrix used for both sides of the heat exchanger, half of the frontal face area would be used for each flow stream. The ratio A_c/A_f reflects the flow blockage caused by the frontal area of fins and plates. The face area is

$$A_f = \frac{\dot{w}}{1800\,(A_c/A_f)} \left(\frac{D_h}{\mathrm{Re}\mu}\right)_{\mathrm{Ref}} \qquad (4\text{-}102)$$

The length is

$$L = \frac{\dot{q}}{\dot{q}_{\mathrm{Ref}}\, A_f} \left(A_f L\right)_{\mathrm{Ref}} \qquad (4\text{-}103)$$

Heat exchanger weight is,

$$W_{HX} = WF_{HX} A_f L \rho_{HX} \tag{4-104}$$

where WF_{HX} is the ratio of heat exchanger weight to heat exchanger core weight and includes headers, fittings, and support attachments. The resultant scaling laws for heat exchanger weight and volume are

$$W_{HX} = WF \frac{\dot{q}}{\dot{q}_{Ref}} (A_f L)_{Ref} \rho_{HX} \tag{4-105}$$

$$= 1.3 \frac{\dot{q}}{14.7} (0.0048 \times 1.49) \; 3,300$$

$$W_{HX} = 2.07 \; \dot{q}, \text{ kg} \tag{4-105a}$$

$$V_{HX} = \frac{W_{HX}}{\rho_{HX}} = \frac{2.07}{3,300} \dot{q}$$

or,

$$V_{HX} = 0.626 \times 10^{-3} \; \dot{q}, \text{ m}^3 \tag{4-105b}$$

Pressure drop for the reference heat exchanger is given by Equation 4-38. For these heat exchangers the miscellaneous pressure drop is quite small compared to that caused by the core, and for constant Reynolds numbers Equation 4-38 indicates a pressure drop essentially proportional to L:

$$\Delta P_{freon} = (\Delta P_{freon})_{Ref} \frac{L}{L_{Ref}} \tag{4-106a}$$

$$\Delta P_{H_2O} = (\Delta P_{H_2O})_{Ref} \frac{L}{L_{Ref}} \tag{4-106b}$$

And the resultant scaling laws for pressure drop are

$$\Delta P_{freon} = \frac{0.033}{1.49} \times L = 0.022 \; L \; \frac{kg}{m^2} \qquad (4\text{-}107a)$$

$$\Delta P_{H_2O} = \frac{0.0099}{1.49} \times L = 0.00675 \; L \; \frac{kg}{m^2} \qquad (4\text{-}107b)$$

4.3.3.5 Cooling and Heating Loop Tubing

Tubing or piping is needed to link the components which require liquid heating and cooling. The weight and volume of this tubing may be conveniently computed by analytical means with due considerations for the spacecraft geometry. Tube size should be selected to yield minimum overall weight to the vehicle and the following items must be considered:

1. Tubing weight
2. Pumping power (from friction loss and bend loss)
3. Spacecraft location of components (tubing length).

An analysis was performed to determine the tube diameter which would result in minimum overall weight. The resultant equation is,

$$3.28D\,(0.0715\rho D + 1)^{0.2} = \frac{5.02\, W^{0.6}\, P^{0.2}}{\rho^{0.4}} \qquad (4\text{-}108)$$

where

ρ = fluid density, kg/m^3

D = tube inside diameter, m

W = coolant flow rate, kg/sec

P = power penalty factor, $kg/watt_e$.

Tubing length depends upon the vehicle dimensions and the complexity and number of components in the vehicle life support system. The following assumptions were made in developing a model for the tubing length:

1. Tubing length to and from radiator is three times vehicle diameter for each cabin.
2. Vehicle length is twice the vehicle diameter
3. Power penalty factor equal to 0.23 kg/watt$_e$ (1/2 lb/watt$_e$)
4. Total tube lengths among life support equipment in each cabin is as follows:
    - A. 15.2m (50 ft) for open systems
    - B. 22.9m (75 ft) for partially closed systems
    - C. 38.2m (125 ft) for closed systems

Using these assumptions tubing length, weight and volume are as follows:

$$L = (15.2 + 0.786\ V^{0.333})\ N,\ \text{m (open systems)} \qquad (4\text{-}109a)$$

$$L = (22.9 + 0.786\ V^{0.333})\ N,\ \text{m (partially closed systems)} \qquad (4\text{-}109b)$$

$$L = (38.2 + 0.786\ V^{0.333})\ N,\ \text{m (closed systems)} \qquad (4\text{-}109c)$$

$$W_t = 22L\,(D + 0.89 \times 10^{-3}),\ \text{kg} \qquad (4\text{-}110)$$

$$W_f = \frac{\pi}{4}\rho L D^2,\ \text{kg} \qquad (4\text{-}111)$$

$$V_t = \frac{\pi L}{4}(D + 0.89 \times 10^{-3})^2,\ \text{m}^3 \qquad (4\text{-}112)$$

where

L = Tubing length, m

V = Vehicle volume, m^3

N = Number of occupied cabins

W_t = Tubing weight, kg

W_f = Fluid weight, kg

V_t = Tubing volume, m^3

Pressure drop in tubing is determined by assuming: (1) one 90° bend every 2 ft and (2), turbulent flow. The pressure drop may then be given as:

$$\Delta P = 7.7 \times 10^{-9} \frac{LW^2}{\rho D^4} + 1.9 \times 10^{-9} \frac{\mu^{1/4} W^{7/4}}{D^{19/4} \rho}, \text{ kg/m}^2 \qquad (4\text{-}113)$$

where

W - coolant flow rate, kg/hr

ΔP - pressure drop, kg/m^2

μ - viscosity, kg/meter-hr

4.3.3.6 Liquid Circulation Pumps

Pumps are provided in the cooling loop, heating loop, and radiator loop to circulate fluid through the various included components. Two types of pumps have been considered for space application, i.e., centrifugal and gear type. These are electrical motor driven and may include either the alternating current or the brushless dc type. The brushless dc type normally is more efficient; however, it is less developed than the ac type. Performance information from available pump-motor units has been plotted and equations for weight, volume, and power were developed from the data. These data are from component manufacturers. The developed equations are.

$$WT = 0.0104\ W\ \Delta P^{0.625}, \text{ kg} \qquad (4\text{-}114)$$

$$V = WT/1670, \text{ m}^3 \qquad (4\text{-}115)$$

$$P = 0.0272\,Q\Delta P/\eta, \; kW_e \tag{4-116}$$

$$\eta_{ac} = 0.30 - 0.175^{-Q\Delta P/2.38} \tag{4-117}$$

$$\eta_{dc} = 0.38 - 0.214^{-Q\Delta P/3.89} \tag{4-118}$$

where

WT - weight of pump-motor unit, kg

V - volume of pump-motor unit, m^3

W - weight flow of coolant, kg/hr

ΔP - pressure drop, kg/cm^2

P - power, kW_e

Q - coolant volume flow, m^3/hr

η - efficiency of motor pump unit

The subscripts indicate the motor type:

ac - alternating current

dc - direct current

4.3.4 Thermal Control Subsystem Miscellaneous Equipment

The thermal control subsystem has a significant amount of associated miscellaneous equipment which must be included in life support system equipment weight and volume determinations. A general list of this equipment follows:

1. Pressure switches
2. Temperature control valves
3. Temperature sensors
4. Accumulators
5. Reservoirs
6. Throttling valves
7. Disconnects
8. Diverter valves
9. Mounts and brackets
10. Shutoff valves
11. Check valves

This equipment and its characteristics were obtained from Reference 4-49 and engineering judgments have been made regarding items which must be scaled because of the requirements of the cooling or heating systems. Generally, items which contain flow passages for the main coolant streams require scaling. Items in this category include valves and disconnects. In scaling, the weight flow per unit area is held constant and length of component is assumed not altered. Coolant flow rate can then be assumed to be proportional to total heat load and the valve and disconnect weight and volume then are directly proportional to total vehicle heat load. Coolant reservoirs serve primarily to provide backup fluid for thermal expansion or leakage. Since these needs are expected to be related closely to total vehicle heat load, reservoir capacity also may be assumed to be directly proportional to vehicle heat load. If the reservoir is a thin shelled sphere and designed from a stress standpoint, the reservoir weight and volume are directly proportional to vehicle heat load. The equations which follow, include the miscellaneous equipment, as listed and result from the scaling assumptions described above

$$W_{HL} = 2.05 + 0.554\,Q_{HL},\ \text{kg} \tag{4-119}$$

$$V_{HL} = 0.00153 + 0.00075\,Q_{HL},\ \text{m}^3 \tag{4-120}$$

$$W_{CL} = 8.56 + 0.761\,Q_{CL},\ \text{kg} \tag{4-121}$$

$$V_{CL} = 0.00685 + 0.00757\,Q_{CL},\ \text{m}^3 \tag{4-122}$$

where

W = weight, kg

V - volume, m^3

Q - heating or cooling load, kW_t

subscripts

HL - heating loop

CL - cooling loop

4.4 WATER SUPPLY SUBSYSTEM

The water supply subsystem consists of the water supplies for the crew and vehicle needs, means to collect water from various vehicle sources, and provisions for the recovery or treatment of any waste water to meet the same needs. Depending upon the availability of water from spacecraft sources, it may be necessary to supply stored sources of water for some missions or to supply storage facilities when an excess occurs.

For this study, the process equipment such as water recovery units have been sized on the basis of the crew activity levels and the number of crewmen in each cabin. The equipment weight, volume, and required power have been obtained by using a daily average of the water to be processed. Small surge tanks are provided to average variations in water collection rates. Some capacity over-design is necessary to allow for day to day process rate variations and to permit maintenance shutdown periods. These have been included in the developed process equipment scaling laws. During an emergency operation, the water recovery function ceases and a stored supply of emergency water is used by the crew. Additionally, during any failure of the liquid cooling circuitry in the Thermal Control Subsystem, stored water is supplied to a water evaporator for use as a heat sink. Emergency water for crew use is considered to be stored in the normal use tanks. Water for the emergency water evaporator is stored in a separate tank.

The Water Supply mass balances and the scaling law development are presented in the following order:

- Water Supply Subsystem Mass Balance
- Water Recovery Methods
- Storage tanks
- Sterilization equipment
- Tubing, pumps, and miscellaneous equipment

4.4.1 Water Supply Subsystem Mass Balance

A water mass balance is a necessary part of the water supply subsystem. Figure 4-50 shows the flow of water between the various components and indicates the interfaces with other subsystems. Water collected from the

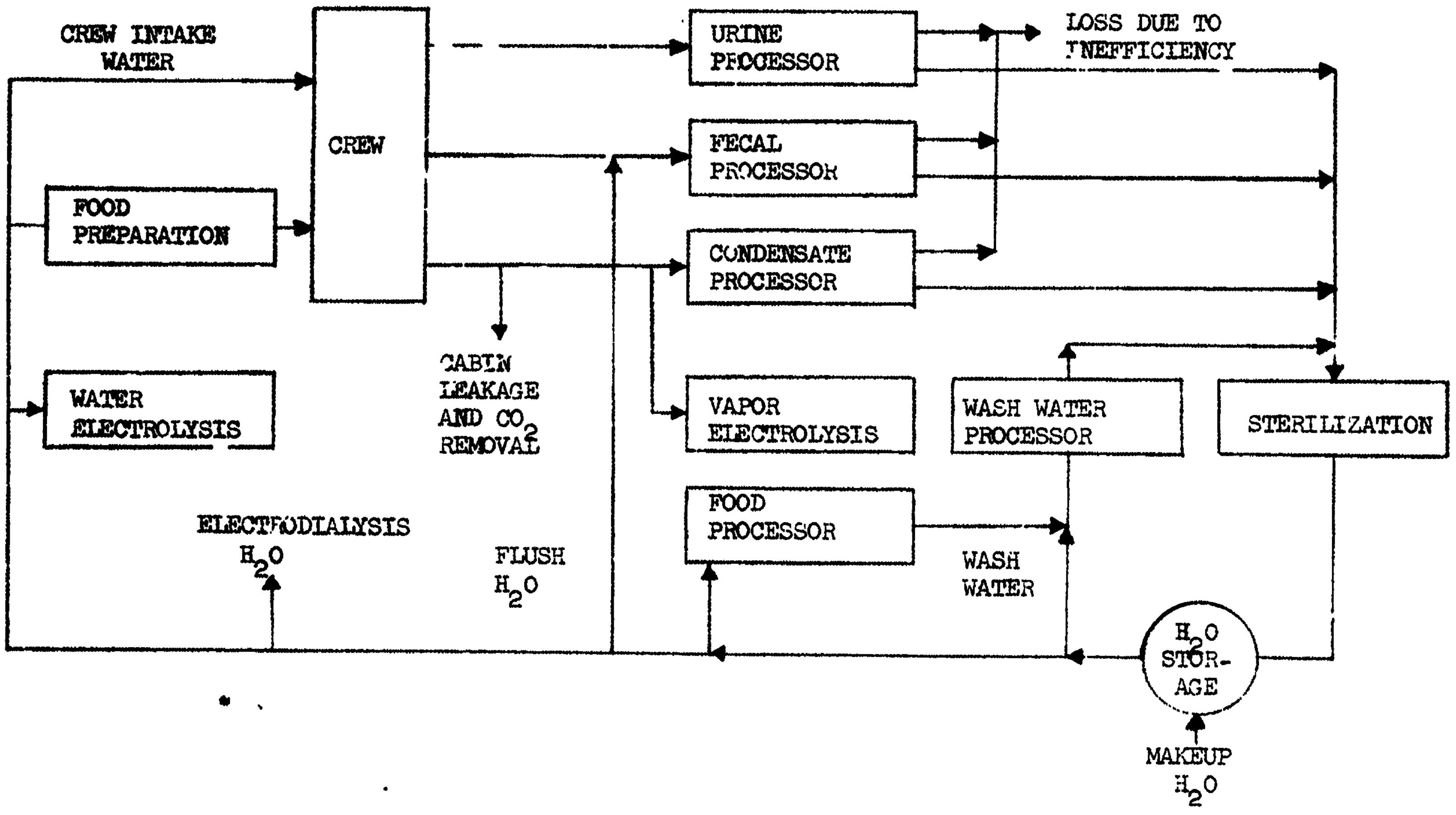


Figure 4-50. Water Flow Diagram.

various sources is either recovered, rejected overboard, or stored. Flush water must be added to the fecal water for some methods of fecal collection. Condensate comes from the water vapor in the cabin atmosphere and consists largely of the water vapor generated by crewmen and it may include trace amounts from process equipment. A small amount of cabin water vapor is lost overboard due to leakage, but large amounts may be used by a vapor electrolysis unit. In the usual process, excess cabin water vapor is condensed in the dehumidifying condenser in the atmosphere purification loop. Water lost because of recovery inefficiency or not recovered is regarded as accumulated material. If sufficient water is not recovered to supply all required vehicle functions, then makeup water is necessary and will be provided. If there is excess water, it is stored as accumulated waste material. In this study, water is necessary for the following functions.

1. Crew intake
2. Waste flush
3. Electrodialysis and vacuum desorbed molecular-sieve CO_2 removal units
4. Food processor
5. Electrolysis
6. Washing

Water is generated within the vehicle by the following processes:

1. Crew metabolism
2. Lithium hydroxide and carbonation cell CO_2 removal units
3. Oxygen recovery unit
4. Food processor

Process heat is removed from the operational vapor pyrolysis and air evaporation water recovery processes by the circulating coolant. Heat also is required for some of these processes and may be obtained either by electrical or from a process heating circuit. Any heat rejected to the atmosphere by the water supply subsystem components is considered and included in atmospheric heat loads of the last cabin.

4.4.2 Water Recovery Methods

This functional group consists of the equipment necessary to receive water from the various sources and to remove the contaminants. The four sources of water are (1) urine, (2) condensate, (3) fecal water, and (4) wash water. Water may be recovered by any of the following methods:

1. Air evaporation
2. Electrodialysis
3. Vapor pyrolysis
4. Multifiltration
5. Vapor compression

Each water source may be processed by a different method or the water may not be recovered at all. Fecal water is considered to be processed only by vapor compression. Future development may permit feasible fecal water recovery by other methods. Besides water processing equipment, the water recovery functional groups include feed tanks, pretreatment and post-treatment tanks, structure and plumbing, transfer pumps, and processed water tanks. Waste water tanks are part of the Waste Management Subsystem.

4.4.2.1 Air Evaporation

In this process, wicks placed in an evaporator are soaked with waste water, heated air passes over the wicks absorbing the water vapor and carries it to a condenser where it is condensed and collected.

The air evaporation process considered is the single-stage, adiabatic, closed cycle type. A schematic diagram for this system is shown in Figure 4-51. Water from the waste water storage tank, together with injected pretreatment chemical, are admitted to a pressurized feed tank. When the wick wetness decreases to a certain level, a temperature sensor actuates a solenoid valve and a measured batch of pretreated water is admitted from the batch feed tank. Microswitches, activated by the batch feed tank as it empties, are used to activate solenoid valves to refill the batch and pressure feed tanks and dispense the pretreatment chemical. The pretreatment chemical selected for use in this model is a 47.3% aqueous solution with

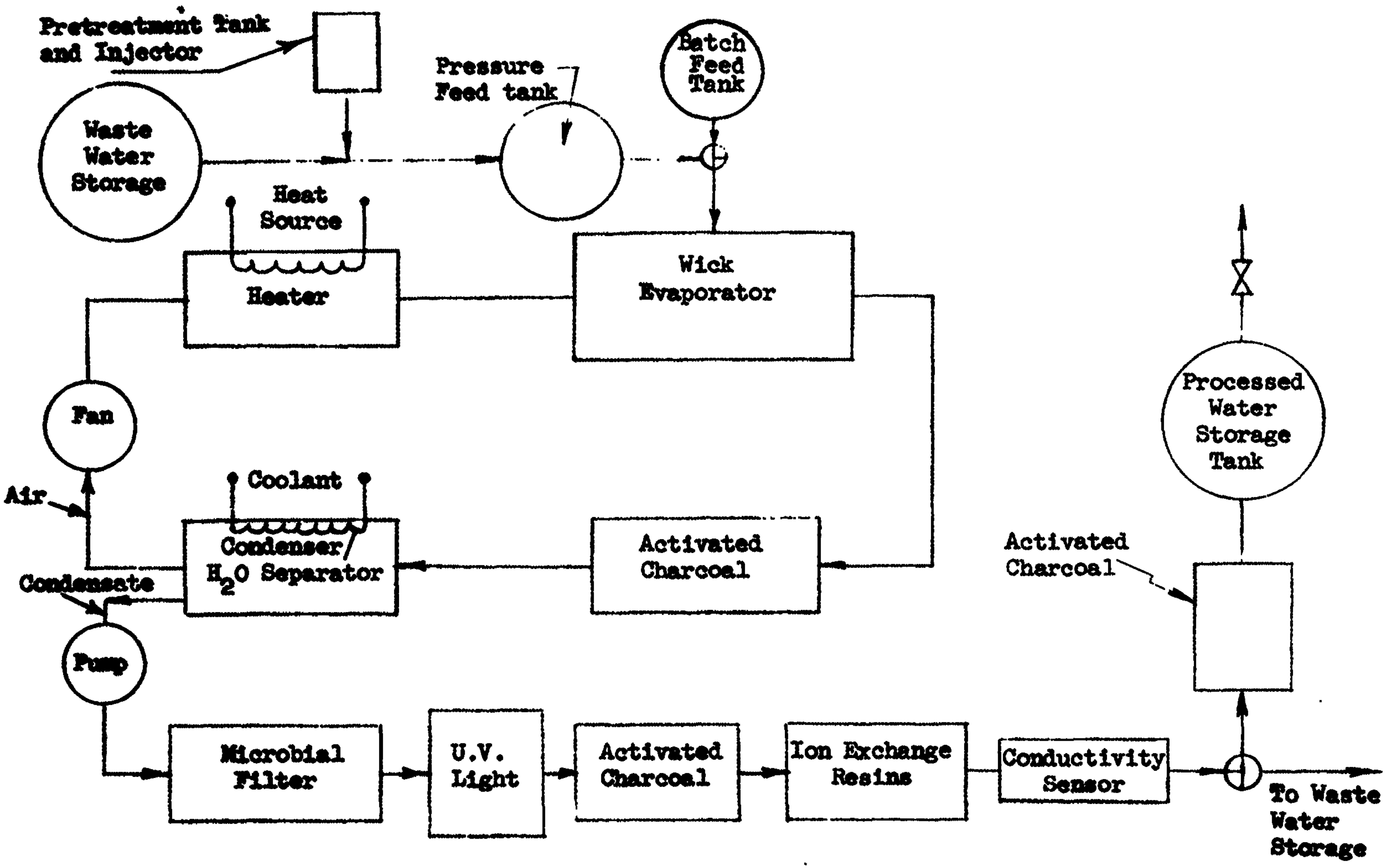


Figure 4-51. Closed Loop Air Evaporation Water Recovery System

39.8% sulfuric acid, 9.8% chromium trioxide, and 3.1% copper sulfate. The required amounts of pretreatment chemical to be used with urine, wash water, or condensate can be calculated from the formulas given in Table 4-32.

Table 4-32

DESIGN SCALING LAWS FOR AN AIR EVAPORATION WATER RECOVERY SYSTEM (page 1 of 2)

(Closed Air Cycle)

I. SYSTEM UTILIZING HEATING FLUID HEAT SOURCE

System Weight = $2.04 + 0.209\,\bar{w}_H + 3.1\,(\bar{w}_H)^{0.5}$ kg

System Volume = $4.5 \times 10^{-2}\,(\bar{w}_H)^{0.565}\ \mathrm{m}^3$

System Power Requirement = $10 + 4.22\,\bar{w}_H$ watts_e

Gas Flow = $4.7\,\rho_G \bar{w}_H$ kg/hr

Heat Rejection to Atmosphere = $Q_{RA} = 9.0\,\bar{w}_H$ watts_t

Heat Rejection to Coolant = $Q_{RC} = 31.0\,\bar{w}_H$ watts_t

II. SYSTEM UTILIZING ELECTRICAL HEAT SOURCE

System Weight = $2.04 + 0.157\,\bar{w}_H + 3.1\,(\bar{w}_H)^{0.5}$ kg

System Volume = $4.5 \times 10^{-2}\,(\bar{w}_H)^{0.565}\ \mathrm{m}^3$

System Power Requirement = $10 + 33.4\,(\bar{w}_H)$ watts_e

Gas Flow = $4.7\,\rho_G \bar{w}_H$ kg/hr

Heat Rejection to Atmosphere, $Q_{RA} = 9.0\,\bar{w}_H$ watts_t

Heat Rejection to Coolant, $Q_{RC} = 31.0\,\bar{w}_H$ watts_t

III. EXPENDABLE WEIGHTS, INDEPENDENT OF HEAT SOURCE

Wick Expendable Weight = $7.0 \times 10^{-3}\,\bar{w}_{H1} + 37 \times 10^{-5}\,\bar{w}_{H2} + 37 \times 10^{-5}\,\bar{w}_{H3}\ \frac{\mathrm{kg}}{\mathrm{day}}$

Table 4-32 (page 2 of 2)

$$\text{Pretreatment Chemical Weight} = 4.0 \times 10^{-3}\,\bar{w}_{H1} + 9.0 \times 10^{-4}\,\bar{w}_{H2} + 9.0 \times 10^{-4}\,\bar{w}_{H3}\ \frac{kg}{day}$$

$$\text{Air Charcoal Weight} = 4.0 \times 10^{-3}\,\bar{w}_{H1} + 15 \times 10^{-4}\,\bar{w}_{H2} + 15 \times 10^{-4}\,\bar{w}_{H3}\ \frac{kg}{day}$$

$$\text{Water Charcoal Weight} = 2.0 \times 10^{-4}\,\bar{w}_{H1} + 75 \times 10^{-5}\,\bar{w}_{H2} + 75 \times 10^{-5}\,\bar{w}_{H3}\ \frac{kg}{day}$$

$$\text{Ion Exchange Resin Weight} = 1.0 \times 10^{-4}\,\bar{w}_{H1} + 5.0 \times 10^{-4}\,\bar{w}_{H2} + 5.0 \times 10^{-4}\,\bar{w}_{H3}\ \frac{kg}{day}$$

$$\text{Microbial Filter Weight} = 5.0 \times 10^{-4}\,\bar{w}_{H1} + 8.0 \times 10^{-5}\,\bar{w}_{H2} + 8.0 \times 10^{-5}\,\bar{w}_{H2}\ \frac{kg}{day}$$

IV. EXPENDABLE VOLUMES, INDEPENDENT OF HEAT SOURCE

$$\text{Wick Expendable Volume} = 570 \times 10^{-7}\,\bar{w}_{H1} + 31 \times 10^{-7}\,\bar{w}_{H2} + 31 \times 10^{-7}\,\bar{w}_{H3}\ \frac{m^3}{day}$$

$$\text{Pretreatment Chemical Volume} = 31 \times 10^{-7}\,\bar{w}_{H1} + 93.5 \times 10^{-8}\,\bar{w}_{H2} + 93.5 \times 10^{-8}\,\bar{w}_{H3}\ \frac{m^3}{day}$$

$$\text{Air Charcoal Volume} = 216 \times 10^{-7}\,\bar{w}_{H1} + 75.0 \times 10^{-7}\,\bar{w}_{H2} + 75.0 \times 10^{-7}\,\bar{w}_{H3}\ \frac{m^3}{day}$$

$$\text{Water Charcoal Volume} = 1090 \times 10^{-8}\,\bar{w}_{H1} + 37.3 \times 10^{-7}\,\bar{w}_{H2} + 37.3 \times 10^{-7}\,\bar{w}_{H3}\ \frac{m^3}{day}$$

$$\text{Ion Exchange Resin Volume} = 181 \times 10^{-8}\,\bar{w}_{H1} + 87.5 \times 10^{-8}\,\bar{w}_{H2} + 87.5 \times 10^{-8}\,\bar{w}_{H3}\ \frac{m^3}{day}$$

$$\text{Microbial Filter Volume} = 31 \times 10^{-7}\,\bar{w}_{H1} + 49.6 \times 10^{-8}\,\bar{w}_{H2} + 49.6 \times 10^{-8}\,\bar{w}_{H3}\ \frac{m^3}{day}$$

Note: w_{H1} is urine water in kilograms/day
w_{H2} is wash water in kilograms/day
w_{H3} is condensate water in kilograms/day

A fan circulates the vapor and air through the system. A heater, utilizing either a hot fluid or electrical energy, heats the air to approximately 50.6°C (123°F) before it is admitted to the evaporator. Water in the wicks is evaporated, by absorbing its heat of vaporization from the hot circulation air. The water vapor increases the dew point of the entering air from approximately 5.6°C (42°F) to 18.9°C (66°F). An activated charcoal bed filters the moist air before it is admitted to the condenser/H_2O separator. The condenser is cooled by circulating coolant at 4.4°C (40°F) to condense the water vapor. The condensate is separated from the air stream in a gas-liquid separator and the air is circulated through the system. A small liquid pump is used to pump the reclaimed water through a microbial filter, UV light, activated charcoal, and ion exchange resin bed. The purity of the water is then checked by being passed through a conductivity sensing cell. If the conductivity level of the water is unacceptable, a solenoid valve diverts the water for reprocessing. Acceptable water is passed through a second activated charcoal bed to the processed water storage tank. Design scaling laws for the air evaporation system are given in Table 4-31, where $\bar{w}_H$ is the total amount of waste water processed in kg/day. The waste water $\bar{w}_H$, is assumed to be comprised of urine, $\bar{w}_{H1}$, wash water, $\bar{w}_{H2}$, and condensate, $\bar{w}_{H3}$. The cabin atmosphere density is denoted by ρ_G, kg/m^3. Table 4-33 gives a detailed breakdown of a reference 10-man air evaporation water recovery system. These scaled data were based on designs, hardware, and test data from MDAC-WD and Hamilton Standard Division of United Aircraft Corporation (References 4-63 and 4-64).

4.4.2.2 Electrodialysis

The electrodialysis water recovery unit is comprised of the following:

1. Precipitation of urea with a complexing agent
2. Removal of additional organics by activated charcoal
3. Demineralization of solution in an electrodialysis stack

A diagram depicting a typical batch type electrodialysis water recovery unit is shown in Figure 4-52. Waste water from the feed tank together with a measured amount of complexing agent are stored in a holding tank. A series of charcoal filters is used to adsorb the precipitate and any residual organics. A feed pump is used to pump this water through the charcoal beds and to

Table 4-33

DETAILS OF A 10-MAN AIR EVAPORATION UNIT*

(Closed Air Cycle)

Component	Weight (kg)	Power (watts$_e$)	Q_{RA} (watts$_t$)	Q_{RC} (watts$_t$)
Fan and filter	0.90	205	228	
Heater and transport fluid	2.72			
Wick evaporator**	2.72			
Air charcoal bed**	0.90			
Condenser/H_2O separator	3.18			800
Tanks (batch feed and pretreatment and pressure feed)**	2.72			
Condensate pump	0.45	10	9.9	
Microbial filter	0.90			
UV light	0.22	40	40	
Water charcoal beds**	0.45			
Ion exchange resin**	0.45			
Processed water storage tank	1.36			
Valves, sensors and instrumentation	1.81	10	9.9	
Structural supports and plumbing	4.53			
TOTAL	23.31	265	287.8	800

---

*Total unit volume = 28.32 x 10^{-2} m^3

**Container weights only. Weights of wicks, charcoal, pretreatment chemical, and ion exchange are given as expendabies as shown in Table 4-32, Item III.

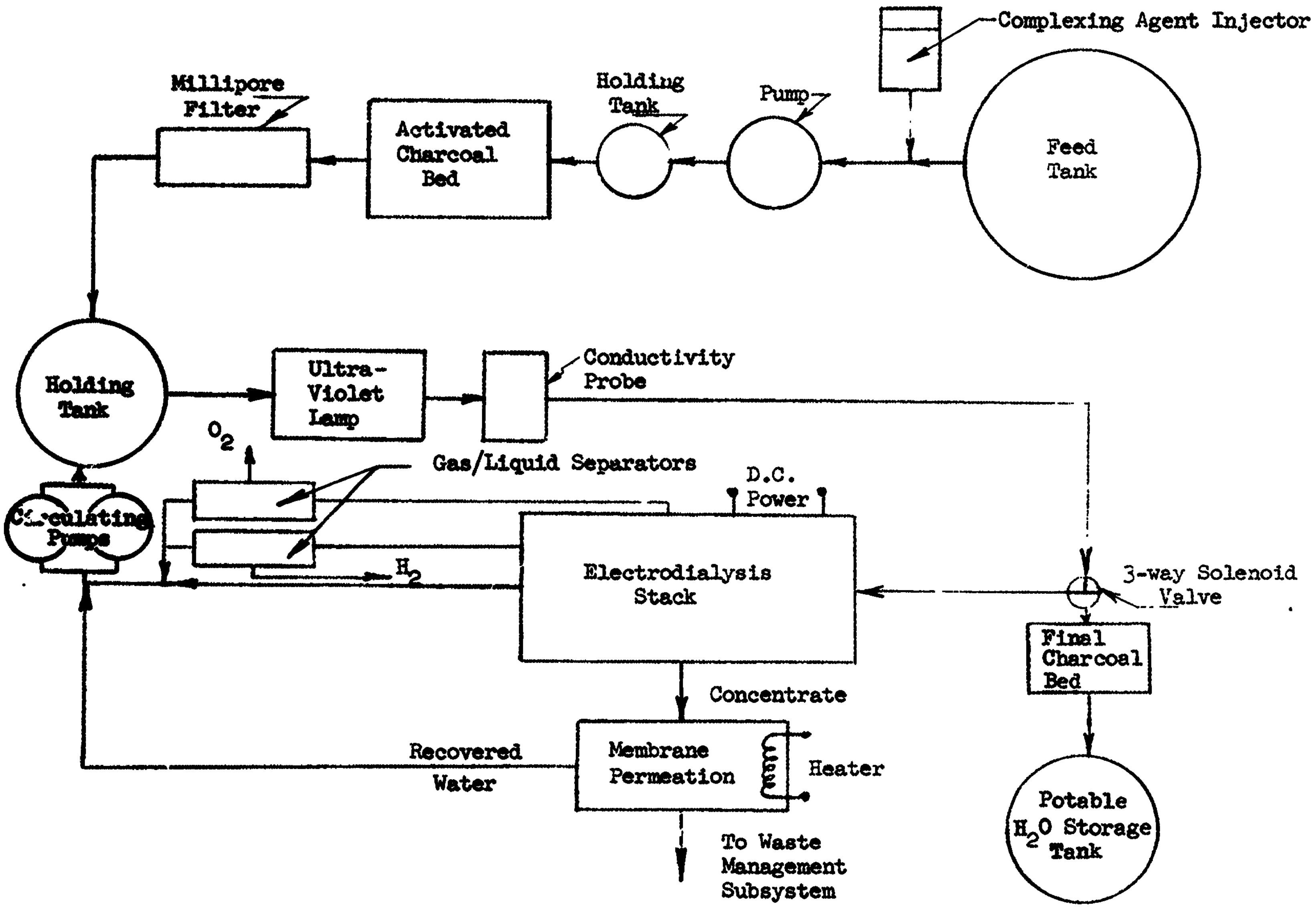


Figure 4-52. Electrodialysis Water Recovery System

deliver it through a millipore filter to a second holding tank. Two circulating pumps, one of which is redundant, are used to circulate the process water throughout the remainder of the electrodialysis unit. Water from the second holding tank is pumped past a UV lamp and then routed to the electrodialysis stack and returned to the holding tank. A conductivity probe, downstream of the UV lamp, is used to test the process water. If found to be of acceptable quality, it is routed to the potable water storage tank. However, if the water quality is unacceptable, a three-way solenoid valve is used to reroute the water to the electrodialysis stack.

In the electrodialysis stack, an electrical potential is applied across the membranes. Under the influence of this potential, positively charged ions pass through the cation permeable membrane, but not through the anion permeable membrane. A similar action but in reverse is imposed by the electrical potential on negatively charged ions. By alternating cells throughout the stack, and passing water through every other cell, both types of ions may be removed from the process water stream, thus purifying it. The ions migrating through the membranes form a concentrate stream in the alternate cells. The process water is repeatedly recycled until an acceptable degree of demineralization is achieved. The conductivity probe determines the purity, and when acceptable, directs the purified water to the storage tank. A membrane permeation unit is used to reclaim the endosmotic water from the concentrate stream. A heater vaporizes the water. A perm-selective membrane passes only the water vapor, thus recovering it. The thick homogeneous liquid residue is transferred to the waste management subsystem and stored. Liquid-gas separators are used to remove any hydrogen and oxygen produced in the electrodialysis stack. Design scaling laws for an electrodialysis urine recovery unit are given in Table 4-34, where $\bar{w}_{H1}$ is the amount of urine processed per man per day. Table 4-35 shows a detailed breakdown of a reference 10-man electrodialysis urine recovery unit. Ion exchange resins were used in this unit for the removal of urea. Scaled data for the 10-man unit were based on designs and hardware by Ionics, Inc., of Cambridge, Massachusetts (Reference 4-65). Ionics also recommended the use of an electrodialysis unit for wash water recovery which is basically similar to the one described above, but requires less

Table 4-34

DESIGN SCALING LAWS FOR ELECTRODIALYSIS URINE WATER RECOVERY UNIT

System Weight = $3.96 + 2.85 (\bar{w}_{H1} N)^{0.665}$ kg

System Volume = $0.018 (\bar{w}_{H1} N)^{0.54}$ m^3

System Power Requirement = $6.6 + 0.96 (\bar{w}_{H1} N)$ watts_e

Heat Rejection to Atmosphere, Q_{RA} = $9.05 + 4.36 (\bar{w}_{H1} N)$ watts_t

EXPENDABLE WEIGHTS:

Complexing Agent Weight = $5 \times 10^{-3} (\bar{w}_{H1} N)$ kg/day

Charcoal Filter Weight = $75 \times 10^{-3} (\bar{w}_{H1} N)$ kg/day

Millipore Filter Weight = $5 \times 10^{-4} (\bar{w}_{H1} N)$ kg/day

EXPENDABLE VOLUMES:

Complexing Agent Volume = $6.21 \times 10^{-6} (\bar{w}_{H1} N)$ m^3/day

Charcoal Filter Volume = $34.4 \times 10^{-5} (\bar{w}_{H1} N)$ m^3/day

Millipore Filter Volume = $31.2 \times 10^{-7} (\bar{w}_{H1} N)$ m^3/day

where:

$\bar{w}_{H1}$ is Urine Weight in kilograms per man per day

N is number of crewmen

expendable material. Design scaling laws and a detailed 10-man reference electrodialysis wash water recovery unit are given in Tables 4-36 and 4-37, respectively. The variable $\bar{w}_{H2}$ indicates the amount of wash water per man per day.

4.4.2.3 Vapor Pyrolysis

This process combines low-temperature vacuum distillation of waste water with high-temperature pyrolysis of the produced vapor. The low temperature,

Table 4-35

DETAILS OF A 10-MAN ELECTRODIALYSIS URINE WATER RECOVERY UNIT(1)

Component	Weight(4) (kg)	Power(2) (watts_e)	Q_{RA}(3) (watts_t)
Electrodialysis stack	4.08	5.5	38
Membrane permeation unit	5.75	3.2	9.9
Feed tank	0.90		
Holding tanks (2)	0.45		
H_2O storage tank	1.36		
Gas liquid separators	5.75		
UV lamp	0.11	2.6	7.6
Pumps (3)	2.95	2.6	7.6
Complexing agent injector	0.45		
Charcoal filter canister	0.45		
Millipore filter canister	0.45		
Valves	0.68		
Instrumentation and controls	2.71	5.0	7.6
Conductivity probe and cell	0.45	1.6	1.5
Structural support and plumbing	4.53		
TOTAL	31.07	20.5	72.2

---

(1) Assumed unit capacity = 14.5 kg/day
(2) 1/24 of total energy requirement
(3) Based on maximum loads
(4) Total unit volume = 8.45×10^{-2} m^3

Table 4-36

DESIGN SCALING LAWS FOR ELECTRODIALYSIS WASH WATER RECOVERY UNIT

System Weight	$= 2.27 + 1.16 (\bar{w}_{H2} N)^{0.795}$ kg
System Volume	$= 0.0087 (\bar{w}_{H2} N)^{0.545}$ m^3
System Power Requirement	$= 3.6 + 0.234 (\bar{w}_{H2} N)$ watts_e
Heat Rejection to Atmosphere, Q_{RA}	$= 4.98 + 1.78 (\bar{w}_{H2} N)$ watts_t
EXPENDABLE WEIGHTS:	
Ion Exchange Resin Weight	$= 33 \times 10^{-4} (\bar{w}_{H2} N)$ kg/day
Charcoal Filter Weight	$= 20 \times 10^{-3} (\bar{w}_{H2} N)$ kg/day
EXPENDABLE VOLUMES:	
Ion Exchange Resin Volume	$= 54 \times 10^{-7} (\bar{w}_{H2} N)$ m^3/day
Charcoal Filter Volume	$= 100 \times 10^{-6} (\bar{w}_{H2} N)$ m^3/day

where:

$\bar{w}_{H2}$ is wash water allotment per man per day

N is number of crewmen

---

low vaporization pressure of the water minimizes the breakdown of urea to ammonia, and the volatilization of organic constituents contained in the waste water. But the water vapor still contains some ammonia and volatile organics. High-temperature catalytic oxidation of this water vapor in a pyrolysis chamber is the means used for producing potable water. A number of prototype units, using various heat sources, have been built and operated by General Electric Company.

A diagram of a batch type vapor pyrolysis water recovery unit, utilizing a transport fluid loop heat source, is shown in Figure 4-53. Water from the feed tank is admitted into the evaporator through a feed metering device. Evaporation of the waste water occurs at 49°C (120°F) and at 0.12 kg/cm^2

Table 4-37

DETAILS OF A 10-MAN ELECTRODIALYSIS WASH WATER RECOVERY UNIT(1)

Component	Weight(4) (kg)	Power(2) (watts$_e$)	Q_{RA}(3) (watts$_t$)
Electrodialysis stack	2.94	1.5	29.3
Membrane permeation unit			
Feed tank	0.90		
Holding tank	0.34		
H_2O storage tank	1.36		
Gas liquid separators			
UV lamp	0.11	2.6	7.6
Pump	1.13	1.2	3.5
Canisters	0.90		
Charcoal filter canister			
Millipore filter canister			
Valves	0.34		
Instrumentation and controls	1.81	2.0	3.5
Conductivity probe and cell	0.45	1.6	1.46
Structural support and plumbing	2.71		
TOTAL	12.99	87.0	45.36

---

(1) Assumed unit capacity = 22.6 kg/day
(2) 1/24 of total energy requirement
(3) Based on maximum loads
(4) Total unit volume = 0.0532 x m^3

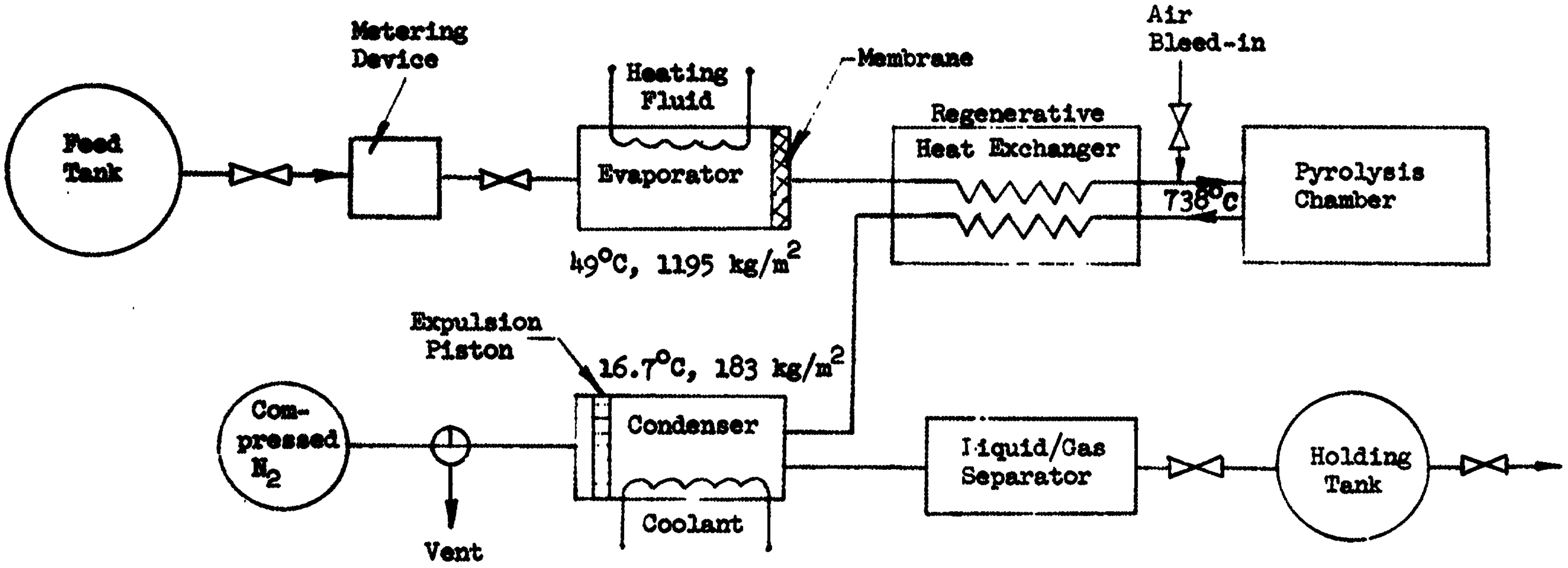


Figure 4-53. Vapor Pyrolysis Water Recovery System

(1.7 psia). The vapor produced flows through a nonwettable membrane which allows only vapor to pass. A regenerative heat exchanger using the products of the pyrolysis chamber heats the vapor to about 738°C (1,360°F) prior to its passage to the pyrolysis chamber. The water vapor, together with some bleed air to provide the necessary oxygen, are passed into the pyrolysis chamber. A platinum wire mesh catalyst is used to further heat the vapor to 816°C (1,500°F) and to oxidize the entrained ammonia and volatile compounds. After flowing through the regenerative heat exchanger, the vapor is condensed in the condenser at a temperature of 16.7°C (62°F) and a pressure of 0.0183 kg/cm^2 (0.26 psia). Condensate and noncondensable gases are periodically forced out of the condenser by a piston actuated by compressed gas. In the liquid-gas separator, the noncondensable gases are isolated and vented to space, and the purified water is delivered to the holding tank. Design scaling laws for the vapor pyrolysis water recovery system are given in Table 4-38 for units utilizing either hot transport fluid or electrical heaters for a heat source. Table 4-39 gives a detailed breakdown of a reference 10-man vapor pyrolysis unit. These data for the 10-man unit were based on equipment hardware and designs by the General Electric Company (Reference 4-66).

4.4.2.4 Multifiltration

The multifiltration process is suited mainly for reclamation of slightly contaminated water, such as wash or condensate water. A schematic diagram of a typical multifiltration system is shown in Figure 4-54. Waste water from the feed tank is metered into the system by means of a solenoid operated metering device. Water passes first through a particulate filter where solid particles are removed, and then through an activated charcoal filter where the organic substances are adsorbed. A mixed ion exchange resin bed is provided for the removal of ionic species from the contaminated water. After leaving the ion exchange resin bed, water flows through a microbial filter, and past a UV light where bacteria and microorganisms are removed or killed. A second activated charcoal filter is downstream of the UV light. Processed water is then stored in a tank. For water to be used

Table 4-38

DESIGN SCALING LAWS FOR VAPOR PYROLYSIS WATER RECOVERY UNIT(*) (page 1 of 2)

I. SYSTEM USING HOT HEAT TRANSPORT FLUID:

System Weight = $1.81 + 2.11\ (\bar{w}_H)^{0.68}$ kg

System Volume = $0.00935\ \bar{w}_H^{\ 0.615}\ m^3$

System Electrical Power Requirement = $10 + 1.84\ \bar{w}_H$ watts_e

Heat Rejection to Atmosphere, Q_{RA} = $9.99 + 8.6\ \bar{w}_H$ watts_t

Heat Rejection to Coolant, Q_{RC} = $32.1\ \bar{w}_H$ watts_t

II. SYSTEM USING ELECTRICAL HEATERS:

System Weight = $1.81 + 2.21\ (\bar{w}_H)^{0.565}$ kg

System Volume = $0.00935\ (\bar{w}_H)^{0.615}\ m^3$

System Power Requirement = $10 + 32.5\ (\bar{w}_H)$ watts_e

Heat Rejection to Atmosphere, Q_{RA} = $9.9 + 8.6\ (\bar{w}_H)$ watts_t

Heat Rejection to Coolant, Q_{RC} = $32.1\ (\bar{w}_H)$ watts_t

III. EXPENDABLE WEIGHTS FOR BOTH SYSTEM TYPES:

Pyrolysis Chamber Atmosphere Loss = $2.18 \times 10^{-3}\ \rho_G\ \bar{w}_{H1} + 1.12 \times 10^{-3}\ \rho_G\ \bar{w}_{H2} + 1.12 \times 10^{-3}\ \rho_G\ \bar{w}_{H3}$ kg/day

Microbial Filter Expendable Weight = $5 \times 10^{-4}\ \bar{w}_{H1} + 8 \times 10^{-5}\ \bar{w}_{H2} + 8 \times 10^{-5}\ \bar{w}_{H3}$ kg/day

Activated Charcoal Expendable Weight = $2 \times 10^{-3}\ \bar{w}_{H1} + 75 \times 10^{-5}\ \bar{w}_{H2} + 75 \times 10^{-5}\ \bar{w}_{H3}$ kg/day

---

Table 4-38 (page 2 of 2)

IV. EXPENDABLE VOLUMES FOR BOTH SYSTEM TYPES;

Microbial Filter Expendable Volume $= 31.2 \times 10^{-7}\ \bar{w}_{H1} + 50 \times 10^{-8}\ \bar{w}_{H2} + 50 \times 10^{-8}\ \bar{w}_{H3}\ m^3/day$

Activated Charcoal Expendable Volume $= 100 \times 10^{-7}\ \bar{w}_{H1} + 37.5 \times 10^{-7}\ \bar{w}_{H2} + 37.5 \times 10^{-7}\ \bar{w}_{H3}$

(*) Notes: $\bar{w}_H$ = Total amount of waste water processed in kg/day.
$\bar{w}_{H1}$, $\bar{w}_{H2}$, $\bar{w}_{H3}$ indicate amounts of urine, wash water, and condensate processed, in kg/day, respectively.
ρ_G = Density of cabin atmosphere, kg/m^3.

in washing, an injector dispenses a measured amount of benzalkonium chloride into the water prior to its storage. Benzalkonium chloride acts both as a detergent and a germicide.

Design scaling laws for multifiltration water recovery units, for both wash water and condensate, are given in Table 4-40. $\bar{w}_{H2}$ and $\bar{w}_{H3}$ denote the rates of wash water and condensate processed in kilograms per day. The basic equipment hardware weight, volume, and power requirements are almost identical for either wash water or condensate systems. The weight of a benzalkonium chloride dispenser, of 0.23 kg (0.5 lb) for a 10-man unit, was found to be so small that it is included in the expendable weight of material supplied. Table 4-41 gives a detailed breakdown of a reference 10-man multifiltration unit. Data for the 10-man unit were based on designs, hardware, and test results by Electric Boat Division of General Dynamics Corporation (Reference 4-67).

4.4.2.5 Vapor Compression

Vapor compression is a distillation process characterized by a technique which conserves the latent heat of vaporization. It utilizes the heat evolved by condensing the output vapor to vaporize the input feed water. The vapor is compressed to a higher pressure, achieving a higher condensing temperature

Table 4-39

DETAILS OF A 10-MAN VAPOR PYROLYSIS WATER RECOVERY UNIT(1)

Component	Weight(2) (kg)	Power (watts$_e$)	Q_{RA} (watts$_t$)	Q_{RC} (watts$_t$)
Evaporator	1.82		96.5	
Electrical Heater	0.90	833		
Hot fluid heater and loop	6.32			
Heat exchanger	0.90			
Pyrolysis chamber	1.36	50	138	
Condenser	1.36			876
Liquid-gas separator	0.45			
Microbial filter	0.23			
Feed tank	0.90			
Storage tank	1.36			
Activated charcoal filter canister	0.45			
Valves, controls and instrumentation	1.82	10	9.9	
Structural supports and plumbing	4.53			
TOTAL				
System using heating fluid	21.50	60	244.4	876
System using electrical heaters	16.08	893	244.4	876

---

(1) Based on a process flow of 27.1 kg/day
(2) Total unit volume = 0.071 m^3 (2.5 ft^3)

than that required for evaporation and making the heat transfer process possible. The condensate reclaimed in this process requires that it be passed through a microbial filter, activated charcoal, and ion exchange resin to render it potable.

A number of vapor compression water recovery units have been built. These have been mostly of the batch feed type. Some continuous feed type designs

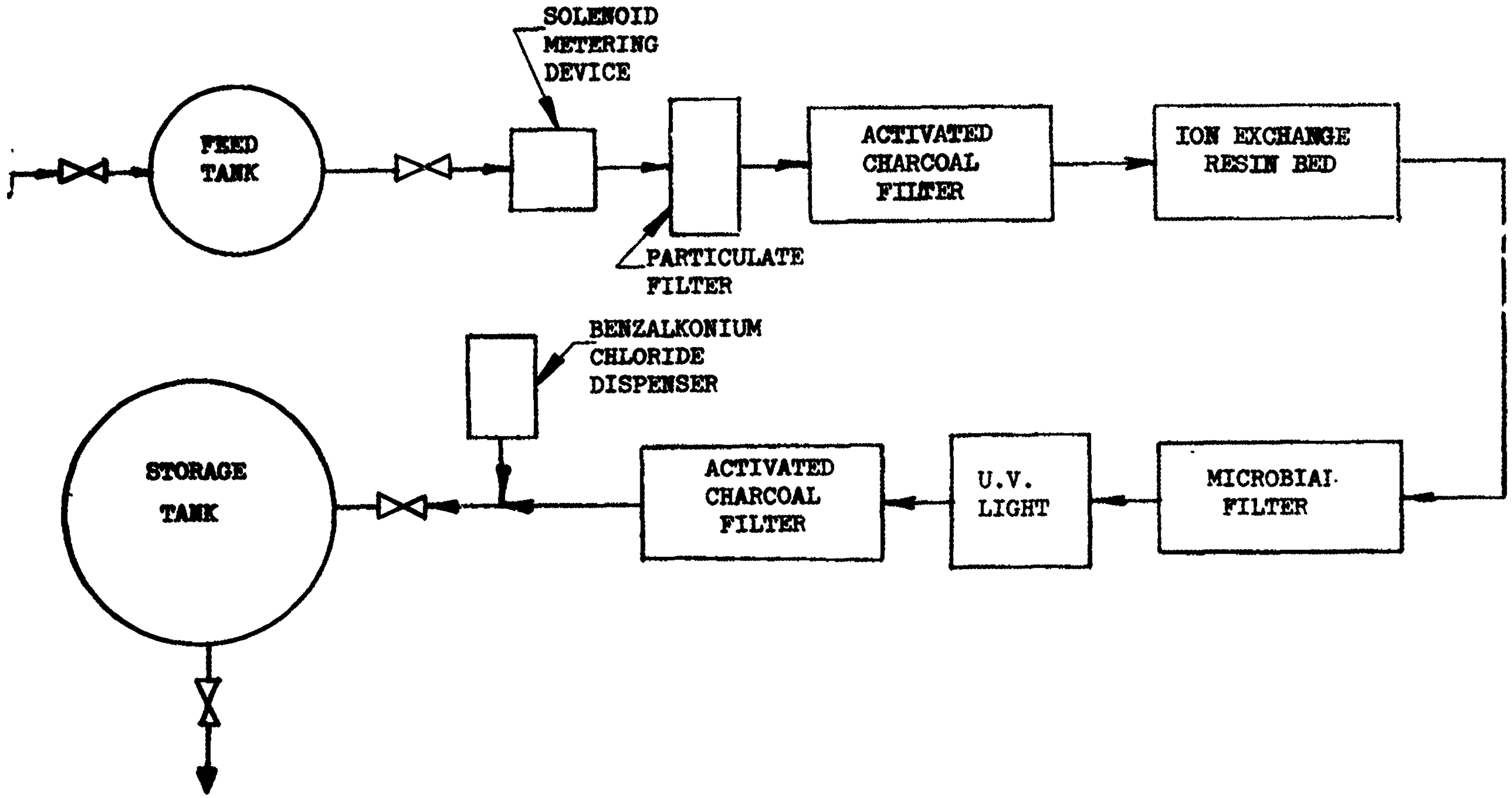


Figure 4-54. Multifiltration Water Recovery System

Table 4-40

DESIGN SCALING LAWS FOR MULTIFILTRATION WATER RECOVERY UNIT (page 1 of 2)

I. WASH OR CONDENSATE WATER:

System Weight = $2.02 + 1.19 (\bar{w}_H)^{0.77}$ kg

System Volume = $0.011 (\bar{w}_H)^{0.665}$ m^3

System Power Requirement = $10 + 1.77 (\bar{w}_H)$ watts_e

Heat Rejection to Atmosphere, Q_{RA} = $9.9 + 1.77 (\bar{w}_H)$ watts_t

II. EXPENDABLES FOR WASH WATER SYSTEM:

Particulate Filter Expendable Weight = $3 \times 10^{-4} (\bar{w}_{H2})$ kg/day

Microbial Filter Expendable Weight = $5 \times 10^{-4} (\bar{w}_H 2)$ kg/day

Activated Charcoal Filters (2) Expendable Weight = $55 \times 10^{-4} (\bar{w}_{H2})$ kg/day

Ion Exchange Resin Expendable Weight = $8 \times 10^{-3} (\bar{w}_{H2})$ kg/day

Benzalkonium Chloride Expendable Weight = $5 \times 10^{-4} (\bar{w}_{H2})$ kg/day

Particulate Filter Expendable Volume = $18.7 \times 10^{-7} (\bar{w}_{H2})$ m^3/day

Microbial Filter Expendable Volume = $31.2 \times 10^{-7} (\bar{w}_{H2})$ m^3/day

Activated Charcoal Filters (2) Expendable Volume = $344.4 \times 10^{-7} (\bar{w}_{H2})$ m^3/day

Ion Exchange Resin Expendable Volume = $12.5 \times 10^{-6} (\bar{w}_{H2})$ m^3/day

Benzalkonium Chloride Expendable Volume = $6.21 \times 10^{-7} (\bar{w}_{H2})$ m^3/day

III. EXPENDABLES FOR CONDENSATE WATER SYSTEM:

Particulate Filter Expendable Weight = $3 \times 10^{-4} (\bar{w}_{H3})$ kg/day

Microbial Filter Expendable Weight = $5 \times 10^{-4} (\bar{w}_{H3})$ kg/day

Ion Exchange Resin Expendable Weight = $1 \times 10^{-3} (\bar{w}_{H3})$ kg/day

Activated Charcoal Filters (2) Expendable Weight = $25 \times 10^{-4} (\bar{w}_{H3})$ kg/day

Table 4-40 (page 2 of 2)

Particulate Filter Expendable Volume = $18.8 \times 10^{-7}\ (\overline{w}_{H3})\ m^3/day$

Microbial Filter Expendable Volume = $31.3 \times 10^{-7}\ (\overline{w}_{H3})\ m^3/day$

Ion Exchange Resin Expendable Volume = $156 \times 10^{-8}\ (\overline{w}_{H3})\ m^3/day$

Activated Charcoal Filters (2) Expendable Volume = $156 \times 10^{-7}\ (\overline{w}_{H3})\ m^3/day$

where:

$\overline{w}_{H2}$ is weight of wash water processed, kilograms per day
$\overline{w}_{H3}$ is weight of condensate processed, kilograms per day

have been proposed but none have been built. The mathematical model derived here, a batch type, is based mainly on units built by the Marquardt Corporation. These units may reclaim fecal water as well as urine, wash, or condensate water. A typical unit is shown schematically in Figure 4-55. Each batch of preheated waste water is vaporized and condensed during a 10-min cycle. The evaporator operates at 49°C (120°F) and a pressure of approximately 0.12 kg/cm^2 (1.7 psia). The condensation of the steam takes place at 54°C (130°F) and approximately 0.155 kg/cm^2 (2.2 psia). The slurry residue is removed from the surface of the evaporator after each batch by a motor-driven mechanical wiper which transfers the residue to a solids collector located at the outer extreme of the rotating drum assembly. The amount of water lost in the solids is assumed to be 20% of the solids weight. The solids are removed by removing an expendable solid collector tray which lines the inner surface of the drum assembly and which can be stored. The unit is purged of noncondensable gases to the vacuum of space. The waste water feed is automatic, and it admits the next batch to the evaporator when the pressure in the evaporator drops below a given value, indicating little waste water is available for vaporization. The unit startup requires that the initial feed batch be heated electrically to the proper evaporator temperature of 49°C (120°F). Subsequent batches are heated by the regenerative heat exchanger. This heat source is supplemented when required by electrical

Table 4-41

DETAILS OF A 10-MAN MULTIFILTRATION WATER RECOVERY UNIT(1)

Component	Weight(3) (kg)	Power (watts$_e$)	Q_{RA} (watts$_t$)
Feed tank	0.90		
Solenoid metering device	0.68		
Particulate filter canister	0.45		
Microbial filter canister	0.45		
UV light	0.23	40	40
Activated charcoal filters canisters(2)	2.71		
Ion exchange resin canister	2.56		
Benzalkonium chloride injector (2)	0.23		
Storage tank	1.36		
Valves, sensors, and controls	1.81	10	10
Structural supports and plumbing			
TOTAL	11.38	50	50

---

(1) Based on a rate of 22.6 kg/day of condensate or wash water.
(2) Not necessary for condensate recovery units.
(3) Total unit volume = 9.9×10^{-2} m^3.

heaters. Once the unit has been in operation for several cycles, sufficient heat is stored to maintain evaporator temperatures without supplemental heat. The amount of liquid in a batch is such that it should form a layer of fluid about 0.6 mm thick. This thickness of liquid is not expected to float under zero-gravity conditions.

The condensate is circulated by a pump through a regenerative heat exchanger to warm the feed water, and through the microbial filter,

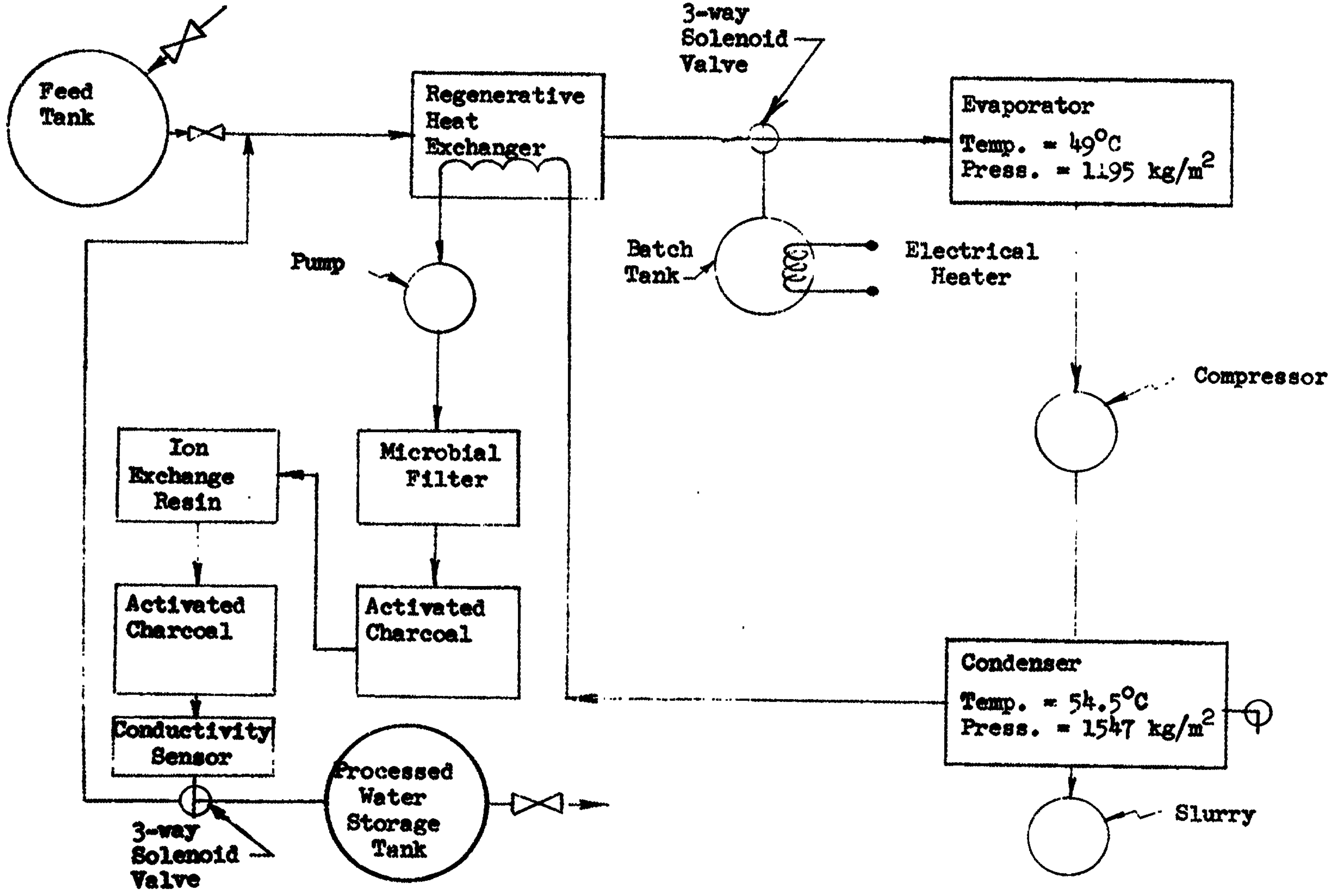


Figure 4-55. Vapor Compression Water Recovery System

activated charcoal, ion exchange resin, and a second activated charcoal bed. A conductivity probe is used to test the processed water, and if found of acceptable quality, the water is passed to the potable water storage tank. If the water quality is unacceptable, a three-way solenoid valve is used to recycle the batch. Table 4-42 gives the design scaling laws for the vapor compression water recovery system. The variables $\bar{w}_{H1}$, $\bar{w}_{H2}$, $\bar{w}_{H3}$, and $\bar{w}_{H4}$ indicate the rates of urine, wash, condensate, and fecal water processed in kilograms per day. The sum of all waste water is indicated by $\bar{w}_H$. A detailed breakdown of a reference 10-man vapor compression unit, 38.6 kg/day capacity, is given in Table 4-43. Data for the 10-man unit were based on hardware, test results, and projection estimates by the Marquardt Corporation (References 4-68 and 4-69).

4.4.3 Storage Tanks

Several types of storage tanks must be provided for makeup water, accumulated excess water and emergency water, as well as for holding, batch, or waste storage. Designs have been included for spherical and cylindrical tanks. Each tank is assumed to be equipped with a bladder for phase separation of water and tank pressurizing gas for all missions. This is necessary, from an operational standpoint, because all missions will have some degree of zero or random gravity operation. Spherical tanks normally result in minimum storage weight; however, packaging considerations favor cylindrical tanks in some cases. Scaling laws have been developed for both tank shapes, relying on the data from numerous space qualified water tanks which have been built. Due to the specialized requirements of most of the space qualified tanks, their data were not readily scalable; however, their data could be used as a guide and check on the analytically developed laws. Tank weight and volume scaling laws have been obtained analytically as outlined below. Weights for spherical tanks were obtained by using the thin-shell stress equation, and then calculating the weight of material required. The equation for total weight is thus,

$$WT = \pi D^2 \rho_s t_s + \pi D^2 \rho_b t_b + K_1 \quad , \text{kg} \qquad (4\text{-}123)$$

where

WT = weight of tank, kg

D = diameter of tank, meters

ρ_s = density of shell material, kg/m^3

t_s = thickness of shell, meters

ρ_b = density of bladder, kg/m^3

t_b = thickness of bladder, meters

K_1 = fixed weight allowance for bosses, mounting brackets and miscellaneous hardware, kg

The shell thickness is computed on the basis of the material design stress and the following equation for shell thickness.

$$t_s = \frac{PD}{4S} \quad , \text{m} \qquad (4\text{-}124)$$

where

P = design pressure, kg/cm^2

S = design stress, kg/cm^2

Substituting Equation 4-124 into 4-123, the following expression results

$$WT = \frac{\pi}{4S}\rho_s PD^3 + \pi D^2 \rho_b t_b + K_1 \quad , \text{kg} \qquad (4\text{-}125)$$

Aluminum shell material is assumed. A design pressure of 3.5 kg/cm^2 is used with a stress level of 700 kg/cm^2. Due to handling considerations and launch loads, a minimum value of 0.5 mm will be used for design shell thickness. A bladder thickness of 0.5 mm is used with a typical bladder density of 1,500 kg/m^2.

Volumes of spherical tanks are computed by the simple geometric equation,

$$V = \frac{\pi}{6}D^3 \quad , \text{m}^3 \qquad (4\text{-}126)$$

Table 4-42

DESIGN SCALING LAWS FOR VAPOR COMPRESSION WATER RECOVERY SYSTEM

System Weight $= 5.4 + 13.9 (\bar{w}_H)^{0.475}$ kg

System Volume $= 4.25 \times 10^{-2} + 2.4 \times 10^{-3} (\bar{w}_H)$ m^3

System Power Requirement $= 9.4 (\bar{w}_H)^{0.615}$ watts_ϵ

Heat Rejection to Atmosphere, Q_{RA} $22 + 1.74 (\bar{w}_H)$ watts_t

Microbial Filter Expendable Weight $= 5 \times 10^{-4}\, \bar{w}_{H1} + 8 \times 10^{-5}\, \bar{w}_{H2}$
$+ 8 \times 10^{-5}\, \bar{w}_{H3} + 5 \times 10^{-4}\, \bar{w}_{H4}$ kg

Ion Exchange Resin Expendable Weight $= 1 \times 10^{-3}\, \bar{w}_{H1} + 5 \times 10^{-4}\, \bar{w}_{H2}$
$+ 5 \times 10^{-4}\, \bar{w}_{H3} + 1 \times 10^{-3}\, \bar{w}_{H4}$ kg

Activated Charcoal Expendable Weight $= 2 \times 10^{-3}\, \bar{w}_{H1} + 75 \times 10^{-5}\, \bar{w}_{H2}$
$+ 75 \times 10^{-5}\, \bar{w}_{H3} + 2 \times 10^{-3}\, \bar{w}_{H4}$ kg

Pretreatment Chemical Expendable Weight $= 3 \times 10^{-3}\, \bar{w}_{H1} + 9 \times 10^{-4}\, \bar{w}_{H2}$
$+ 9 \times 10^{-4}\, \bar{w}_{H3} + 3 \times 10^{-3}\, \bar{w}_{H4}$ kg

Microbial Filter Expendable Volume $= 311 \times 10^{-8}\, \bar{w}_{H1} + 49.8 \times 10^{-8}\, \bar{w}_{H2}$
$+ 49.8 \times 10^{-8}\, \bar{w}_{H3} + 311 \times 10^{-8}\, \bar{w}_{H4}$ m^3

Ion Exchange Resin Expendable Volume $= 180 \times 10^{-8}\, \bar{w}_{H1} + 87 \times 10^{-8}\, \bar{w}_{H2}$
$+ 87 \times 10^{-8}\, \bar{w}_{H3} + 180 \times 10^{-8}\, \bar{w}_{H4}$ m^3

Activated Charcoal Expendable Volume $= 108 \times 10^{-7}\, \bar{w}_{H1} + 37.4 \times 10^{-7}\, \bar{w}_{H2}$
$+ 37.4 \times 10^{-7}\, \bar{w}_{H3} + 108 \times 10^{-7}\, \bar{w}_{H4}$ m^3

Pretreatment Chemical Expendable Volume $= 311 \times 10^{-8}\, \bar{w}_{H1} + 93.5 \times 10^{-8}\, \bar{w}_{H2}$
$+ 93.5 \times 10^{-8}\, \bar{w}_{H3}$
$+ 311 \times 10^{-8}\, \bar{w}_{H4}$ m^3

---

where $\bar{w}_{H1}$, $\bar{w}_{H2}$, $\bar{w}_{H3}$, and $\bar{w}_{H4}$ are urine, waste, condensate and fecal water, respectively, in kilograms per day.

Table 4-43

DETAILS OF A 10-MAN VAPOR COMPRESSION WATER RECOVERY SYSTEM

Capacity 38.6 kg/day

Component	Weight[(1)] (kg)	Power (watts_e)	Q_{RA} (watts_t)
Feed tank	1.09		
Vapor compression still	40 0	74.5	73.90
Heat exchanger	0.95		
Heater	0.10	6.1	6.10
Fan and motor	0.20	8.5	8.50
Activated charcoal filters	4.20		
Bacteria filters	2.54		
Sterilizer	2.09		
Resin column	2.31		
Accumulator	1.89		
Flow meter	0.90		
Conductivity meter	1.72	0.7	0.72
pH meter	0.68		
Control and instrumentation	1.70		
Electrical wiring	1.70		
Plumbing	3.66		
Storage tank	9.65		
Structural supports and insulation	10.90		
TOTAL	86.28	89.8	89.22

---

(1) Total Unit Volume = 13.5×10^{-2} m^3

Cylindrical tank weights are determined by a procedure similar to that for spherical tanks. The shell consists of a cylindrical portion and end hemispheres. The cylindrical portion of the tank is the most highly stressed region and the expression for the cylindrical thickness is,

$$t_s = \frac{PD}{2S} \quad , \text{m} \tag{4-127}$$

Substituting this value into an equation for tank weight results in the following equation:

$$WT = \left(\pi DL + \frac{\pi D^2}{2}\right)\left(\frac{PD}{2S}\rho_s + t_b\rho_b\right) + K_1, \text{ kg} \tag{4-128}$$

Assumed bladder characteristics are the same as those of the spherical tanks and the value of K_1 is taken as 2.3 kg.

The expression for cylindrical tank volume is determined from geometric considerations as follows:

$$V = \frac{\pi D^3}{4}\left[\frac{L}{D} - \frac{1}{3}\right] \tag{4-129}$$

4.4.4 Sterilization Equipment

After water is purified in the water recovery unit it is stored. In this state its sterility must be maintained. Two methods considered to be the most promising to maintain water sterility without affecting potability are: treatment with silver ions or pasteurization. The silver ions are added by electrolysis to the water stream as it flows from the water recovery units. Because the silver ions tend to collect on the equipment interior surfaces, the source must be continuously replaced; however, the weight for makeup silver is negligible. The fixed weight of the silver ion generator was estimated based on Reference 4-70 to be 0.5 kg and requires a volume of 0.0003 m^3. The power and expendable requirements for silver ion generator are negligible.

Pasteurization consists of maintaining the water in storage at a temperature of 120°C (250°F). The weight and power quantities involved in pasteurization consist of heater weight, tank insulation, and heater power. As the water is assumed to be stored in the last cabin, the heat which is transferred from the hot tanks in the last cabin to the cabin atmosphere is included in the atmosphere thermal load for that cabin. Electrical power is used to provide pasteurization heat. Weight of the heater is estimated at 0.8 kg and a volume of 0.0005 m^3. Electrical power is that required to raise all water processed to approximately 100°K and to compensate for the heat lost from tanks to cabin atmospheres.

$$Q_{st} = W_{st} C_{H_2O} \Delta T + Q_{ins} \qquad (4\text{-}130)$$

where

Q_{st} = heater power, kW

W_{st} = flow of water to be sterilized, kg/hr

C_{H_2O} = specific heat of water, kW hr/kg°K

ΔT = temperature rise of water, °K

Q_{ins} = heat lost through tank insulation, kW

Tank insulation is needed with pasteurization to prevent large heat losses from the tanks and resulting in excessive power requirements. The thickness of insulation required can be determined by performing a tradeoff study between insulation thicknesses and the equivalent weight of electrical power required by the heat losses. Thin insulation results in low insulation weight but high heater power and increases in loads and capacity of the thermal control system to remove the tank heat transferred to the cabin atmosphere. On the other hand, thick insulation results in high insulation weight but lower heater power and tank heat losses. A tradeoff study using the following assumptions indicated that the required insulation thickness should be about 6.0 cm.

1. Insulation characteristics of fiber glass material:
   Thermal conductivity - 3.46×10^{-5} $kW_t/m°K$
   Insulation density - 160 kg/m^3

2. Thermal control equivalent weight factor - 22.6 kg/kW$_t$
   (Reference 4-71)
3. Heater power equivalent weight factor - 227 kg/kW$_e$
4. Vehicle volume equivalent weight factor - 16 kg/m^3
   (additional vehicle structure to accommodate insulation volume)

Using an insulation thickness of 6.0 cm, the scaling laws for spherical tank insulation are as follows:

$$WT_{ins} = 9.6\ \pi D^2 \left(\frac{L}{D}\right) \quad , \text{kg} \tag{4-131}$$

$$V_{ins} = 0.06\ \pi D^2 \left(\frac{L}{D}\right) \quad , \text{m}^3 \tag{4-132}$$

$$Q_{ins} = 48.0\ \pi D^2 \left(\frac{L}{D}\right) \quad , \text{watts}_t \tag{4-133}$$

$$P_{Heater} = Q_{ins} + 116\ \text{W} \quad , \text{watts}_e \tag{4-134}$$

where

WT_{ins} = insulation weight, kg
D = tank diameter, m
N = number of tanks
V_{ins} = volume of insulation, m^3
Q_{ins} = heat loss through insulation, watts$_t$
P_{Heater} = heater power, watts$_e$
L = length of tank, m

4.4.5 Tubing, Pumps, and Miscellaneous Equipment

The various water supply components are connected with tubing, and since water collection points may be considerably removed from water processing, storage, or use areas, appreciable tubing weights result. Pumps are required to draw the water from the various sources to be stored or processed before distribution. Miscellaneous equipment includes controls, sensors, probes, brackets, and other Water Supply Subsystem equipment not included in the other functions groups above.

Total tubing involved in collection and distribution are primarily a function of vehicle geometry and location of the water processing and storage equipment. The assumption is made that water lines run twice the length of the vehicle in addition to twice the vehicle diameter. It is also assumed that 0.945 cm (3/8 in.) diameter aluminum tubes are used. The line weight volume can be expressed as follows:

$$W_{lines} = 0.0845\,(2\,L_c + 2\,D_c) \quad , \text{kg} \tag{4-135}$$

$$V_{lines} = 0.000636\,W_{lines} \quad , \text{m}^3 \tag{4-136}$$

The characteristics for pumps, fittings and miscellaneous equipment are estimated, but are based on data from Reference 4-72 as follows:

$$W_{misc} = 5.5 \quad , \text{kg} \tag{4-137}$$

$$V_{misc} = 0.0031, \quad \text{m}^3 \tag{4-138}$$

$$P_{misc} = 15 \quad , \text{watts}_e \tag{4-139}$$

4.5 WASTE MANAGEMENT SUBSYSTEMS

The Waste Management Subsystem includes functional groups of components which accomplish collection, disposal, and storage for reclamation or accumulation of CO_2, trace contaminants, urine, fecal material, and refuse.

Removal of CO_2 and trace contaminants is more critical than removal of any other wastes in that comfort and health of crewmen are more immediately affected by the performance of their associated equipment. An atmosphere purification loop is thus provided for each cabin. The CO_2 level is generally controlled to a partial pressure of less than 7.6 mm Hg (0.01 kg/cm^2). The allowable levels for trace contaminants have not been completely established; however, currently accepted values have been used in this study. Control of CO_2 level during emergency conditions is considered to be important enough to warrant the provision for separate CO_2 removal equipment and materials. Subsection 3.1.3 gives a more complete discussion of CO_2 control during emergency conditions.

Collection, disposal, and storage equipment for urine, fecal material, and refuse are assumed to be located in the crew living quarters. As noted in Subsection 3.4.1, these quarters are always assumed to be provided in the last cabin, or highest numbered cabin, of those specified.

The functional methods to be used for CO_2 removal and urine, feces, and refuse management are largely dependent upon the disposal or use of the waste products. The approach taken here has been to select sufficient alternate functional methods to be of most interest to the range of mission durations and levels of ecological closure studied. Selection of a functional method to satisfy a given combination of mission duration and ecological closure also has been determined on the basis of estimates of the equipment probability of success.

Alternate functional methods are provided for CO_2 removal with O_2 and food recovery from collected CO_2 and additional alternate methods are provided for CO_2 removal without O_2 and food recovery from collected CO_2. Alternate functional methods for other wastes consider collected urine to be dumped overboard, accumulated for use as radiation shielding, or stored for further use in water, oxygen, and food recovery processes. Collected fecal material is considered to be accumulated (possibly for use as radiation shielding) or stored for further use in water, oxygen, and food recovery processes. Collected refuse can be used for radiation shielding.

The discussion of the waste management subsystem alternate functional methods considered and the mass and energy balances and scaling law development for each functional waste management method are presented in the following order:

1. Carbon dioxide removal
2. Trace contaminants
3. Urine, feces, and refuse management

4.5.1 Carbon Dioxide Removal

The functional carbon dioxide removal methods are discussed in the following order:

1. Lithium hydroxide
2. Liquid absorption
3. Electrodialysis
4. Solid amines
5. Carbonation cells
6. Molecular sieves

4.5.1.1 Lithium Hydroxide

Of all the carbon dioxide removal methods, LiOH has had the most actual spacecraft application and space flight experience. This is because expendable LiOH possesses a relatively high CO_2 absorption capacity per unit mass of material coupled with a lower than average heat of absorption. LiOH absorbs CO_2 from a gas mixture and in the presence of water vapor.

A cabin relative humidity of 50 to 70% usually provides sufficient water vapor for the absorption reaction to take place. This reaction is given by the equation:

$$2\ \mathrm{LiOH} + \mathrm{CO_2} \longrightarrow \mathrm{Li_2\ CO_3} + \mathrm{H_2O} + 568\ \mathrm{watt_t/hr, kg\ of\ CO_2} \qquad (4\text{-}140)$$

The heat of reaction is based on the assumption that all water produced is evolved as vapor. In case this is not true, the value given would need to be adjusted accordingly. Granular lithium hydroxide has a bulk density of approximately 400 to 448 kg/m^3 (25-28 lb/ft^3) (Reference 4-73).

The following paragraphs give the characteristics of gas flow through LiOH beds and the design scaling laws for the canisters and accessories.

Gas Flow Requirements

A steady-state flow of purified gas of Q_G m^3/min is required to maintain a spacecraft cabin volume of V m^3 at a predetermined level of CO_2, G_{CO_2} kg. if CO_2 is introduced into the cabin at a rate of $(N\,\bar{w}_c)$ kg/day. This may be given by the following relation:

$$Q_G = \frac{(N\bar{w}_c)}{2.73} \times \frac{V}{G_{CO_2}} = \frac{(N\bar{w}_c)}{2.73} \times \left(\frac{RT}{p}\right)_{CO_2}, \quad \mathrm{m^3/min} \qquad (4\text{-}141)$$

where p, R, and T indicate the partial pressure, universal gas constant, and temperature of the subscripted gas. Equation 4-141 may be rewritten, in terms of mass flow:

$$\bar{w}_G = 2.63 \times 10^{-5} \times \frac{M_G\ P_t}{p_{CO_2}} \times (N\bar{w}_c), \quad \mathrm{kg/sec} \qquad (4\text{-}142)$$

where $\bar{w}_G$ and M_G indicate the mass flow and molecular weight of the purified gas, and P_t is the cabin total pressure. The temperature rise incurred by the gas passing through the beds is given by:

$$\Delta T = \frac{250 \times 10^{-6}\ p_{CO_2}}{C_{p_G}\ M_G\ P_t}, \quad {}^\circ\mathrm{C} \qquad (4\text{-}143)$$

Equation 4-143 is based on the fact that all the reaction water evolves as vapor and no heat is transferred to the beds. The specific heat of gas is C_{p_G}. The amount of water, evolved as vapor, from the reaction is given by:

$$\bar{w}_{H_2O} = 0.00776\ (N\bar{w}_c),\ \text{kg/hr} \tag{4-144}$$

The pressure drop through the bed was derived for an optimum bed length using Reference 4-73, and is given by:

$$L = 0.392\ (N\bar{w}_c)^{0.33},\ \text{m} \tag{4-145}$$

If it is assumed that the LiOH has a density of 400 kg/m^3 and a particle size of 6 to 8 mesh (D_p = 0.00275 m); then, the pressure drop through the bed would be given as:

$$\Delta P = 85.100 \times 10^6\ \frac{\mu_G \bar{w}_G}{\rho_G} \times N^{0.667}\ \bar{w}_C^{\,-0.333},\ \text{kg/m}^2 \tag{4-146}$$

Where μ_G, gas viscosity, is in kg/m-sec.

Lithium Hydroxide Design Scaling Laws

The LiOH canister assembly is assumed to be similar to the Apollo unit and is comprised of:

1. A dual canister section which contains the lithium hydroxide charges. Either canister may be opened for replacement of the charges.
2. A three-way, manually operated selector valve which permits isolation of either canister, or full flow to either or both.
3. Two reed-type check valves, one at each canister outlet.
4. A CO_2 sensor, a flow controller, and a valve located upstream of of the canister assembly which controls the amount of gas flow through the beds.

The design scaling laws for the LiOH assembly, based on a CO_2 processing rate of (Nw_c) kg are given in Table 4-44. Canister performance data were obtained from Reference 4-74.

Table 4-44

LiOH SYSTEM DESIGN SCALING LAWS

System Weight = $1.45 + 3.11 (N\bar{w}_c)^{0.5}$

System Volume = $0.0356 (N\bar{w}_c)^{0.5}$

Expendable (LiOH) Weight = $1.25 (N\bar{w}_c)$ kg

4.5.1.2 Liquid Absorption

This process utilizes a liquid solution of potassium carbonate or sodium carbonate, or a mixture of both, to absorb CO_2. The chemical process involved is shown by

$$K_2CO_3 + CO_2 + H_2O \longrightarrow 2KHCO_3 \qquad (4\text{-}147)$$

When the bicarbonate is heated the reaction may be reversed, driving off the CO_2 and converting it back to carbonate capable of absorbing more CO_2.

A schematic of a potassium carbonate absorption system is shown in Figure 4-56. CO_2 laden air from the cabin is admitted to the liquid contactor where the transformation of gaseous CO_2 to the liquid carbonate takes place, and the mass transfer results in a mixture of potassium bicarbonate and purified air. The liquid-gas separator separates the air and returns it to the cabin through an activated charcoal filter. The liquid solution then flows through the regenerative heat exchanger and the heater where the bicarbonate is dissociated to K_2CO_3 and CO_2. Liquid absorbent from the second liquid-gas separator is returned to the regenerative heat exchanger to heat the incoming liquid stream, then cooled and pumped back to the liquid contactor. Water is separated from CO_2 in the condenser-water separator arrangement and is then routed to the liquid stream returning to the liquid contactor. The resulting CO_2 is 21.1°C (70°F) and saturated with water vapor. A cyclic dual bed silica gel unit is then used to remove all moisture from CO_2 to a level of -51.1°C (-60°F) dew point. The carbon dioxide is then stored in the accumulator.

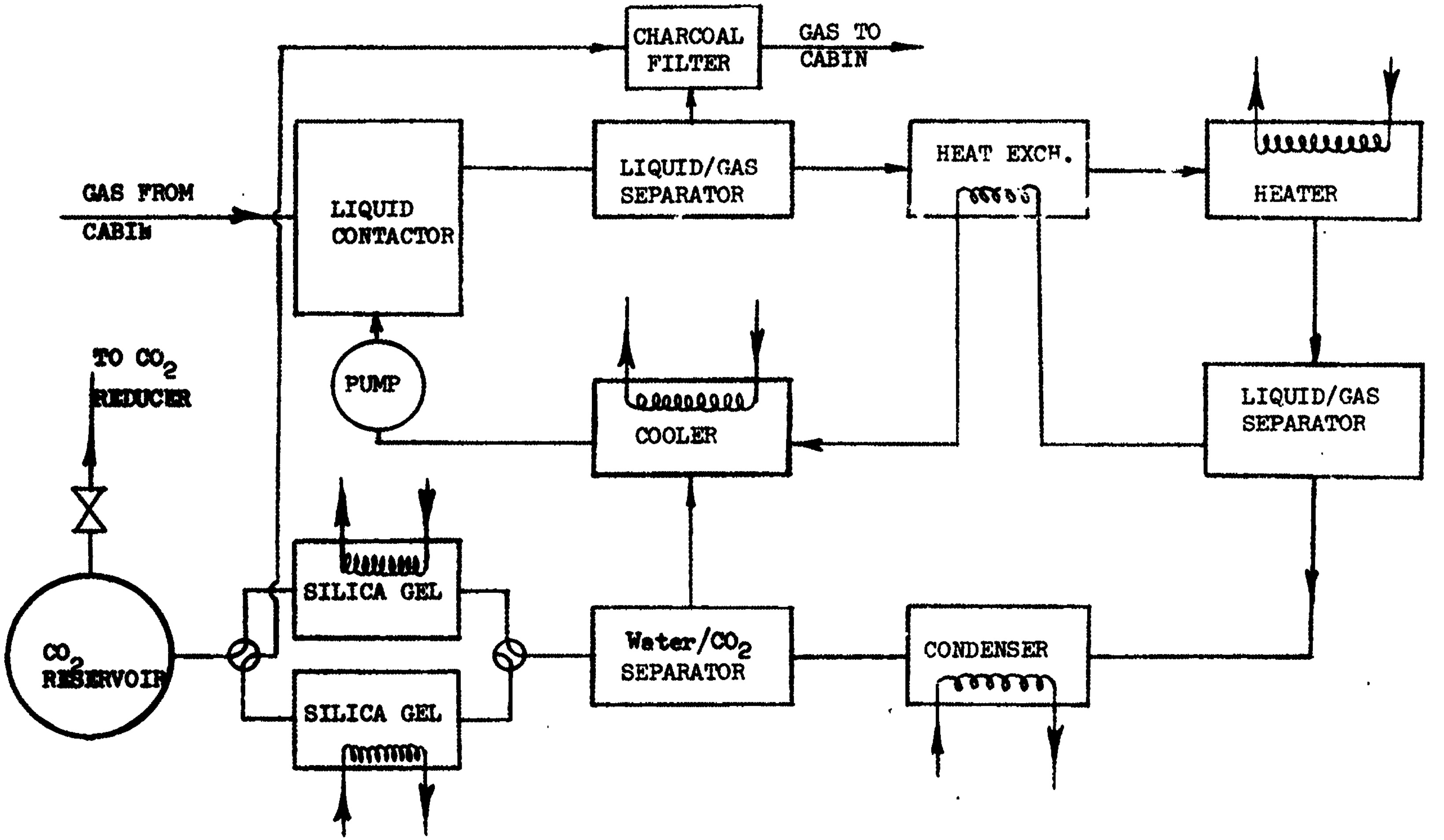


Figure 4-56. Liquid Absorption CO_2 Collector

The condition when CO_2 in the gas stream leaving the absorber is in equilibrium with CO_2 in the liquid stream is defined by the following equation (Reference 4-75):

$$P_{CO_2} = \frac{137\, f_o^{\,2}\, \bar{n}^{\,1.29}}{S\,(1 - f_o)\,(33-1.8t)} \qquad (4\text{-}148)$$

where

P_{CO_2} = partial pressure of CO_2 in gas leaving absorber, mm Hg
$\bar{n}$ = potassium normality of absorbent
S = solubility of CO_2 in H_2O at 1 atmosphere, $\frac{\text{gm-moles } CO_2}{\text{liter}}$
t = temperature, °C
f_o = fraction as bicarbonate leaving the absorber.

In the following design these conditions are assumed:

$\bar{n}$ = 1.0
t = 10°C
P_{CO_2} = 3.8 mm Hg
S = 0.0527 gm-moles/liter

then f_o = 0.432 using Equation 4-148.

Since two moles of $KHCO_3$ are available per mole of CO_2, as indicated by Equation 4-147, and

if
L = flow rate of liquid absorbent, liters/hour.
f_i = initial fraction of potassium as bicarbonate in the absorbent
y_i, y_o = mole fractions of CO_2 in the gas entering and leaving the absorber respectively.
$\eta = \frac{y_i - y_o}{y_i}$ = system absorption efficiency

then, for a potassium normality of 1.0,

$$G\,(y_i - y_o) = \frac{L}{2}\,(0.432 - f_i) \text{ gm-moles of } CO_2 \text{ absorbed/hr} \qquad (4\text{-}149)$$

In addition, the following design assumptions have been made:

$f_i = 0.3$

$\eta = 0.5$

P_{CO_2}, partial pressure of CO_2 entering liquid contactor ≤ 7.6 mm Hg and the equation becomes

$$L = 0.345\ (N\bar{w}_c)\ \text{liters/hr} \tag{4-150}$$

$$G = 0.00597\ P\ (N\bar{w}_c)\ \text{gm-moles/hr} \tag{4-151}$$

Equations 4-150 and 4-151 were used in the design scaling laws for the liquid absorption system given in Table 4-45, where $(N\bar{w}_c)$ is the rate of CO_2 processed in kg and (P) is the total cabin pressure, kg/m^2 (abs).

A detailed breakdown of a 10-man reference unit is shown in Table 4-46. This unit is based upon an engineering design using the relations and assumptions listed above. Little data were found in the literature regarding this type of CO_2 removal system.

Table 4-45

DESIGN SCALING LAWS FOR LIQUID ABSORPTION SYSTEM

System weight $= 6.79 + 3.46\ (N\bar{w}_c) + 7.3\ (N\bar{w}_c)^{0.49}$ **kg**

System volume $= 0.0277\ (N\bar{w}c)^{0.7}\ m^3$

System power requirement $= 110 + 34.3\ (N\bar{w}_c)\ \text{watts}_e$

Heat rejection to atmosphere, $Q_{RA} = 110 + 345\ (N\bar{w}_c)\ \text{watts}_t$

Heat rejection to coolant, $Q_{RC} = 1600\ (N\bar{w}_c)\ \text{watts}_t$

Gas flow $= 0.0132\ P\ (N\bar{w}_c)$ **kg/hr**

Expendable weight $= 0.0618\ (N\bar{w}_c)$ **kg/day**

Expendable volume $= 19.2 \times 10^{-5}\ (N\bar{w}_c)\ m^3/\text{day}$

Fluid heating requirement $= 1430\ (N\bar{w}_c)\ \text{watts}_t$

Table 4-46

DETAILS OF A 10-MAN LIQUID ABSORPTION CO_2 REMOVAL UNIT

Component	Weight* kg (lb)	Power (watts$_e$)	Q_{RA} (watts$_t$)	Q_{RC} (watts$_t$)
Liquid contactor	2.26 (5)			
Liquid/gas separators (3 req)	2.06 (4.5)	60	60	
Heater	1.36 (3)		1,460	
Heating fluid	13.60 (30)			
Condenser	1.81 (4)		293	3,370
Heat exchangers	1.58 (3.5)		293	
Cooler	0.68 (1.5)		1,460	13,100
Pump	0.90 (2)	350		
Cooling fluid	13.60 (30)			
CO_2 reservoir	0.90 (2)			
Silica gel beds (2 req)	5.45 (12)			
Activated charcoal filters	0.45 (1)			
Instrumentation and controls	6.80 (15)	50	50	
Structural support and plumbing	13.60 (30)			
TOTAL	65.05 (143.5)	460	3,616	16,470

*Total unit volume = 14×10^{-2} m^3 (5 ft^3)

4.5.1.3 Electrodialysis

The electrodialysis method collects CO_2 from the gas stream by a combination of absorption and electrodialysis, and some oxygen is generated in the collection process. Prototype units have demonstrated wide ratios of carbon dioxide removal to oxygen generation (Reference 4-76). However, only that type which is basically a CO_2 remover, with minimal O_2 generation, is considered here. The unit's applied current density was found to be an important design parameter, and consequently, it was a necessary variable in the electrodialysis scaling laws.

This process employs ion exchange resins to absorb CO_2 from the cabin atmosphere. CO_2 is then transferred by electrodialysis to a concentrating stream. Oxygen and hydrogen are generated electrolytically at the anode and cathode, respectively. An electrodialysis unit may consist of a number of batteries, each battery consists of five elements: a CO_2 absorber, a concentrator, an anode, a cathode, and selective membranes. A schematic diagram of a typical battery, with a summary of reaction equations, is shown in Figure 4-57. Water is fed to the cathode and anode at a flow rate which exceeds electrochemical requirements, but is sufficient to provide cooling of the unit. Water flow is in the direction of the migrating ions. CO_2 laden cabin atmosphere is fed to the absorber where CO_2 is removed from the air stream.

A schematic of the electrodialysis CO_2 removal unit is shown in Figure 4-58. The blower pumps cabin atmosphere through the humidifier and into the absorber. CO_2 is removed from the saturated air stream and the purified

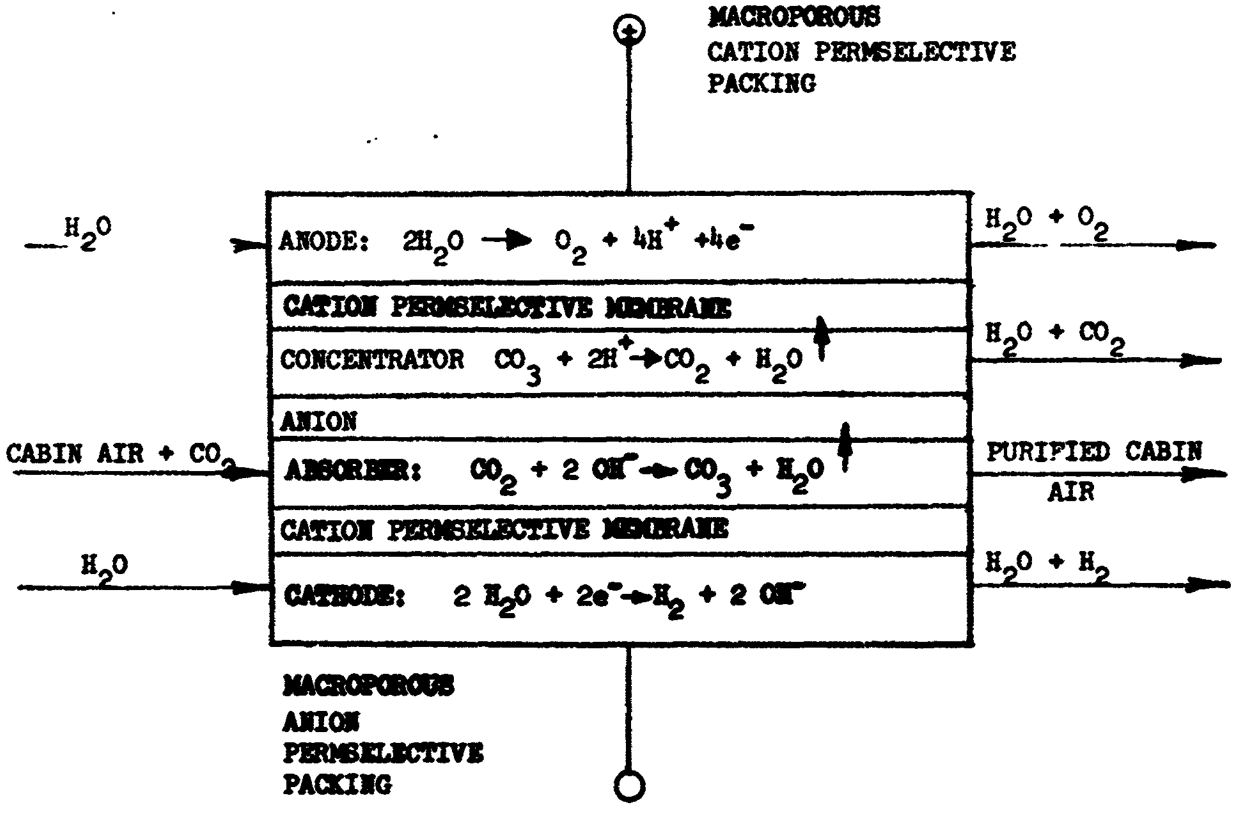


Figure 4-57. Electrodialysis Battery Schematic

air is returned to the cabin. In addition to its cooling effect, water flow is used to sweep oxygen and hydrogen from the anode and cathode respectively. Reference 4-76 indicates that some hydrogen may be in the concentrator's outlet CO_2 stream. Thus, in the case of O_2 recovery from CO_2, the composition of the CO_2 stream must be determined before its admission to the CO_2 reduction unit to insure the accuracy of the CO_2/H_2 mixture composition. The H_2/H_2O stream from the cathode is routed to the gas-liquid separator. Water is returned to the cathode while hydrogen is pumped into an accumulator. Similarly, water from the O_2/H_2O anode stream is returned to the anode and O_2 joins the purified cabin air stream.

Design scaling laws for the electrodialysis unit are given in Table 4-47 where (Nw_c) is the rate of CO_2 processed in kg and I is the current density in amperes/m^2. A detailed breakdown of a 10-man reference unit is shown in Table 4-48. The reference case is based on engineering designs scaled from prototype hardware made by Ionics, Inc. (Reference 4-76).

Table 4-47

DESIGN SCALING LAWS FOR ELECTRODIALYSIS CO_2 COLLECTOR

System Weight = $4.38 + 0.178 (N\bar{w}_c) + 5.68 (N\bar{w}_c)^{0.548} + 12.3 (N\bar{w}_c) I^{-0.705}$ kg

System Volume = $1.41 \times 10^{-2} + 0.372 \times 10^{-3} (N\bar{w}_c) + 0.0107 (N\bar{w}_c{}^{0.548}$

$+ 0.286 (N\bar{w}_c) I^{-0.705}$ m^3

System Power Requirements = $21.6 (N\bar{w}_c) + 13.8 (N\bar{w}_c) I^{0.543}$ watts_e

Heat Rejection to Atmosphere = $21.4 (N\bar{w}_c) + 8.63 (N\bar{w}_c) I^{0.543}$ watts_t

Expendable Water Requirement = $0.285 (N\bar{w}_c)$ kg/day

System Oxygen Credit = $0.253 (N\bar{w}_c)$ kg/day

System Hydrogen Credit = $0.032 (N\bar{w}_c)$ kg/day

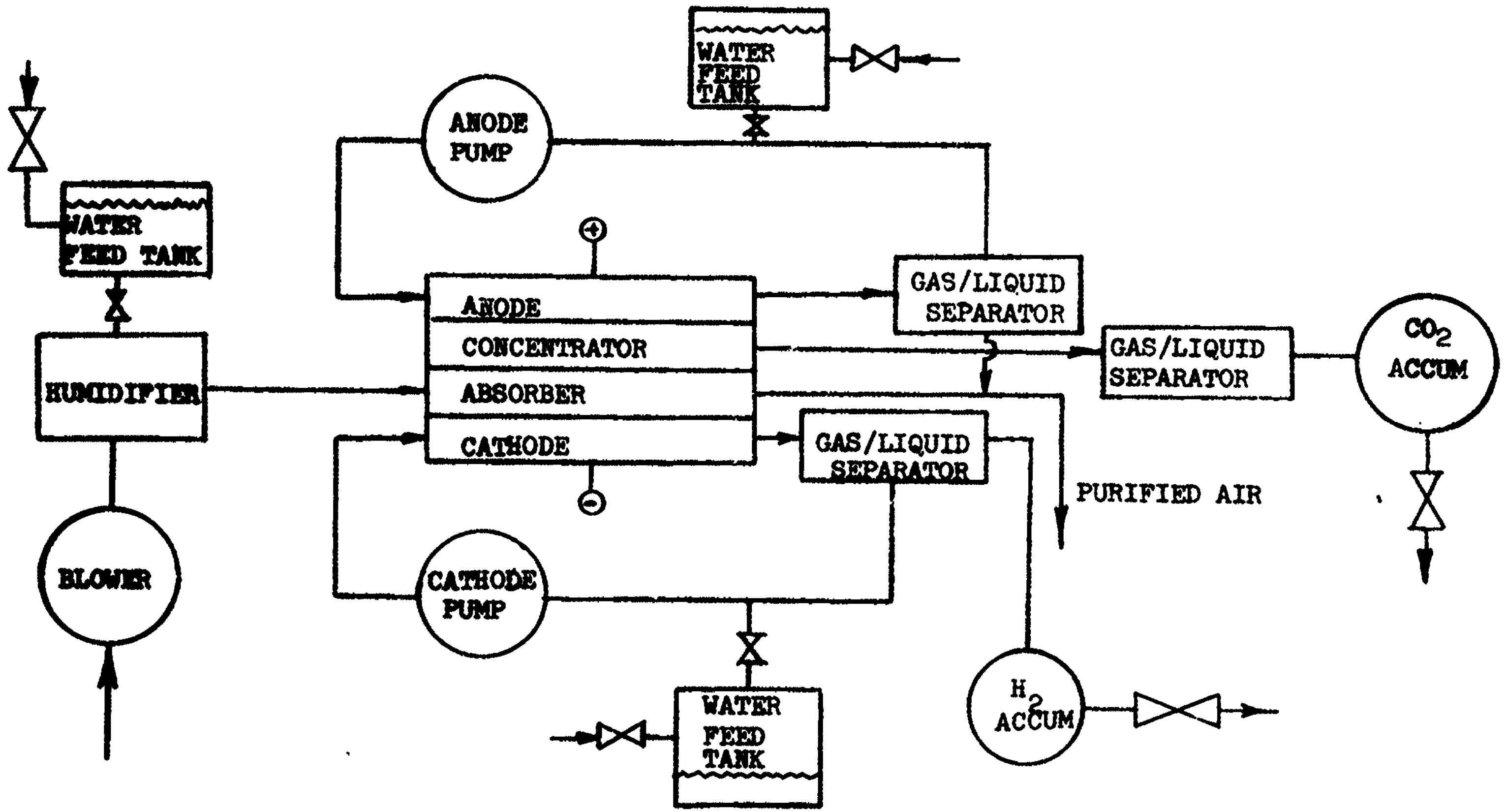


Figure 4-58. Electrodialysis CO_2 Removal Unit

Table 4-48

DETAILS OF A 10-MAN ELECTRODIALYSIS CO_2 COLLECTOR

Component	Fixed Weight* kg	(lb)	Power (watts$_e$)	Q_{RA} (watts$_t$)
Electrodialysis battery (4 req)	$125\ I^{-0.750}$		$141\ I^{0.543}$	$88\ I^{0.543}$
Blower	.81	(4)	100	99
Humidifier	.81	(4)		
Gas-liquid separator (3 req)	2.03	(4.5)		
Feed tanks (3 req)	2.71	(6)		
Liquid pumps (2 req)	2.71	(6)	100	99
CO_2 accumulator	0.90	(2)		
H_2 accumulator	0.90	(2)		
Valves, controls and instrumentation	6.80	(15)	20	19.8
TOTAL	$(28.67 + 125\ I^{-0.705})$		$(220 + 141\ I^{0.543})$	$(217.80 + 88\ I^{0.543})$

*Total Unit Volume = $4.1 \times 10^{-2} + 2.94I^{-0.705}\ m^3$

4.5.1.4 Solid Amines

This process utilizes solid, heat-regenerative CO_2 absorbents for the collection of CO_2 from cabin atmospheres. The solid materials used are organic amines which react with CO_2 to form carbonates. Liquid amines have been used successfully in submarine and commercial applications, and this previous experience led to the investigation of solid amines, preferably as resins, because the gas-liquid phase problems in zero gravity could be avoided. A number of ion exchange resins have been investigated and the results are reported in Reference 4-77. Table 4-49 shows the comparative performance of some solid amines at 100°C. Of interest is the fact that the weakly basic resins have slow absorption rates but show high thermal regeneration characteristics, while on the other hand, strong base resins exhibit high absorption rates with limited regeneration capabilities.

Table 4-49

COMPARISON OF ION EXCHANGE AMINES

Resin	Type	Absorption Rate (mg CO_2/cc resin/hr)	Regeneration (percent)
IR-45 (1)	Weak base	5.4	42
Permutit A (2)	Medium base	5.6	6
Nalcite SAR (3)	Strong base	26.9	6
NRL	DET + Epon 562	20.6	100

(1) Reference 4-77
(2) Reference 4-78
(3) Reference 4-79

The mixture of DET (excess aliphatic amine) and epoxy resin Epon 562, developed by the Naval Research Laboratory (NRL), shows a fairly good absorption rate of 20.6 mgCO_2/cc resin/hr and 100% regeneration at 100°C. Experimental results are given in Reference 4-77 which indicated that swelling the resin with water enhances its CO_2 absorption performance. Air streams with a relative humidity of 50% reportedly contain adequate water for the reaction to proceed. Regeneration of amines may be achieved either by heating and exposure to vacuum, or by heating and purging with a dry CO_2 free gas.

A schematic diagram of a solid amine CO_2 removal system that uses two solid amine beds is shown in Figure 4-59. A timer is used to alternate the beds between adsorption and desorption cycles. Since the amines call for moisture during the adsorption cycle, no desiccant beds are employed. Each of the beds includes an internal tube-and-fin heat exchanger. The timer operates solenoid valves which admit cooling fluid into the heat exchanger during adsorption and heating fluid during desorption. A blower is used to draw cabin atmosphere into the adsorbing bed, after which the purified gas is returned to the cabin. A pump is used during desorption to transfer the CO_2 to the CO_2 reservoir, or to expel it to space.

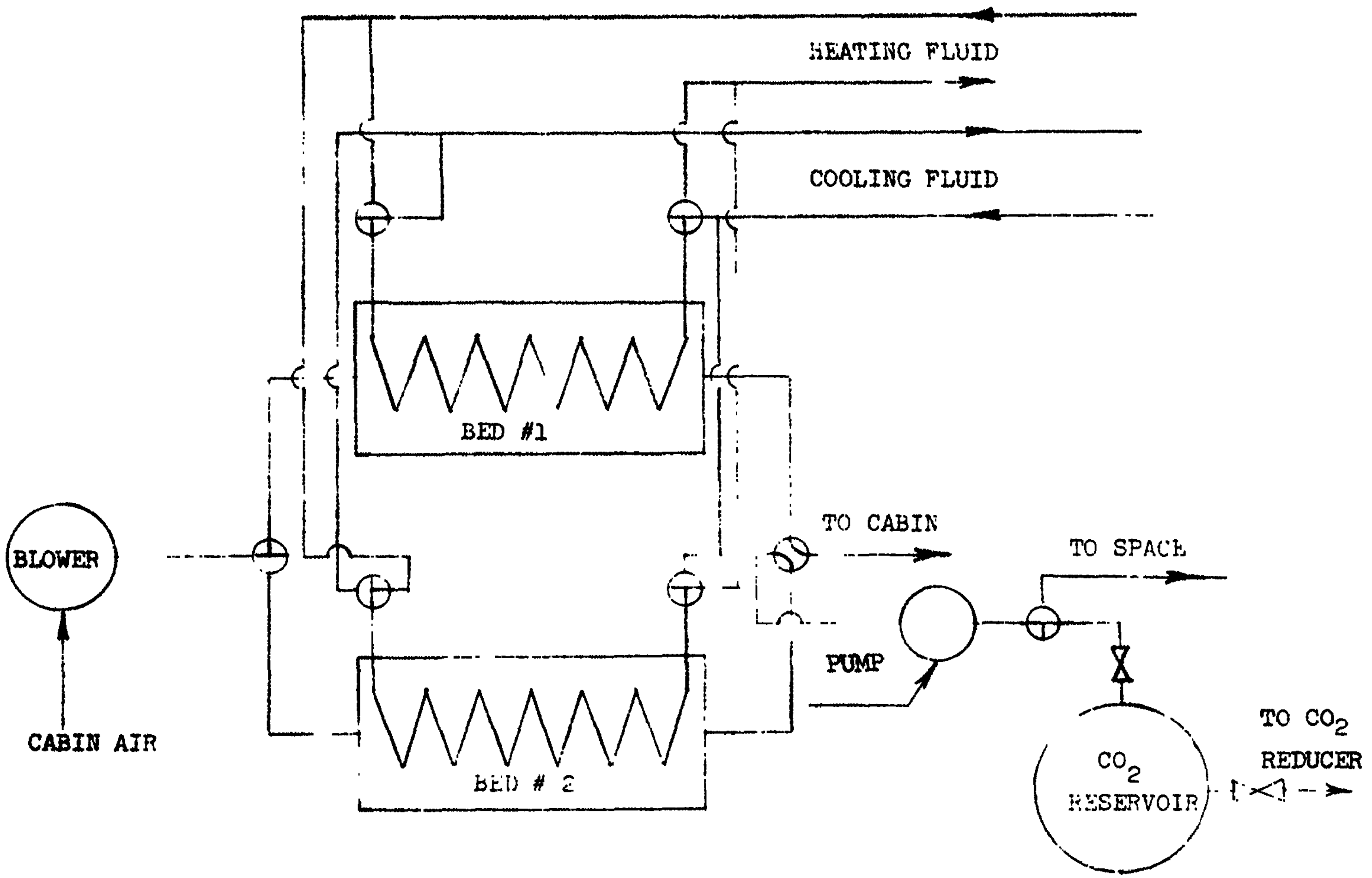


Figure 4-59. Solid Amine CO_2 Collector

Design scaling laws for solid amine CO_2 removal units are shown in Table 4-50, where $N\bar{w}_c$ is the rate of CO_2 processed in kilograms per day. Two sources of heat for the unit operation are included. The first when a hot fluid is used for desorbing the loaded bed and the second for desorption with electrical heaters. A detailed breakdown of a 10-man reference unit is shown in Table 4-51. This reference unit is based on an engineering design scaled from a prototype manufactured by General American Transportation Corporation (Reference 4-80).

4.5.1.5 Carbonation Cells

This is an electrochemical process which utilizes cells consisting of porous electrodes separated by asbestos capillary matrixes which contain an electrolyte such as potassium carbonate (K_2CO_3). The application of

Table 4-50

DESIGN SCALING LAWS FOR SOLID AMINES CO_2 COLLECTOR

A. Unit Utilizing Heating Fluid

System Weight = $2.71 + 5.10 (Nw_c) + 8.6 (N\bar{w}_c)^{0.636}$ kg

System Volume = $0.0521 (N\bar{w}_c)^{0.795}$ m^3

System Power Requirement = $10 + 26 (N\dot{w}_c)$ watts_e

Fluid Heating Requirement = $118 (Nw_c)$ watts_t

B. Unit Utilizing Electrical Heaters

System Weight = $2.71 + 4.44 (N\bar{w}_c) + 8.6 (N\bar{w}_c)^{0.636}$ kg

System Volume = $0.0521 (N\bar{w}_c)^{0.795}$ m^3

System Power Requirement = $10 + 141 (N\bar{w}_c)$ watts_e

C. Unit Utilizing Either Fluid or Electrical Heating

Heat Rejection to Atmosphere = $9.99 + 25.8 (N\bar{w}_c)$ watts_t

Heat Rejection to Coolant = $114 (N\bar{w}_c)$ watts_t

Table 4-51

DETAILS OF A 10-MAN SOLID AMINES CO_2 COLLECTOR

Component	Fixed Weight(1) kg (lb)	Power (watts$_e$)	Q_{RA} (watts$_t$)	Q_{RA} (watts$_t$)
Absorbent material	34 (75)			
Canisters and heat exchangers(2)	22.60 (50)			1,170
Canisters and heat exchangers(3)	20.40 (45)			1,170
Electrical heaters(3)	2.26 (5)			
Heat transport fluid(2)	22.60 (50)	1,173		
Heat transport fluid(3)	11.30 (25)			
Blower	1.81 (4)	100	99	
Vacuum pump	0.90 (2)	163	164	
CO_2 reservoir	3.40 (7.5)			
Controls and instrumentation	2.72 (6)	10	9.90	
Structural support and plumbing	9.05 (20)			
TOTAL (2)	97.8 (189.5)	273	272.9	1,170
(3)	85.84 (214.5)	1,146	272.9	1,170

---

(1) Total unit volume = 34×10^{-2} m^3
(2) Unit utilizes heating fluid for regeneration
(3) Unit utilizes electrical heaters for regeneration

these cells for CO_2 concentration in spacecraft was conceived by TRW, Inc., and supported by NASA Lewis Research Center (Reference 4-81). In addition, NASA Ames Research Center has engaged TRW for the development of an aircraft oxygen generating system which utilizes the same type of cells.

The ion transfer mechanism in the cells has been postulated to be the reaction shown in Figure 4-60. The NASA CO_2 concentrator development program noted in Reference 4-81 did not include the introduction of hydrogen at the anode as is shown in Figure 4-60. Excluding hydrogen results in a high electrical power consumption for the unit. The process diagrammed is more attractive insofar as the unit acts partially as a fuel cell in combining hydrogen and oxygen, and a proportional amount of electrical energy is produced in the reaction.

A system schematic of a carbonation cell CO_2 collection unit is shown in Figure 4-61. The system is composed basically of three cells staged such that the output from each stage is processed further by the following stage. Cabin atmosphere is drawn by the blower through a water vapor exchanger

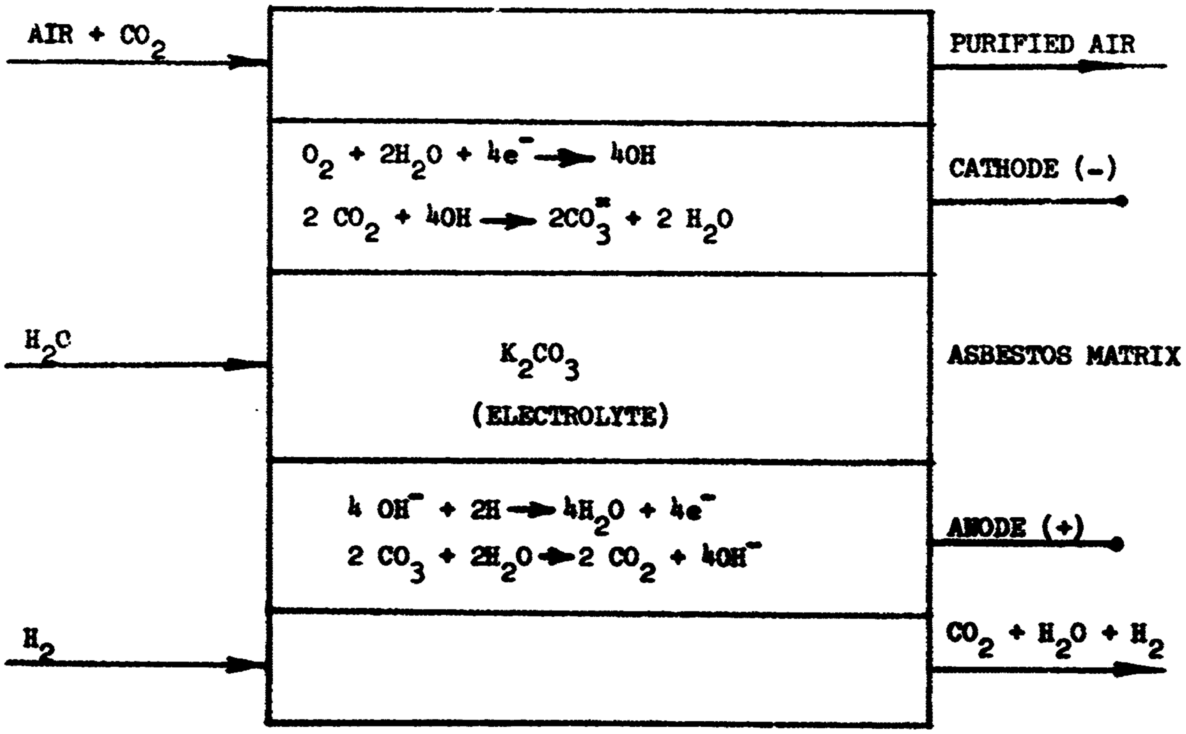


Figure 4-60. Carbonation Cell Reactions

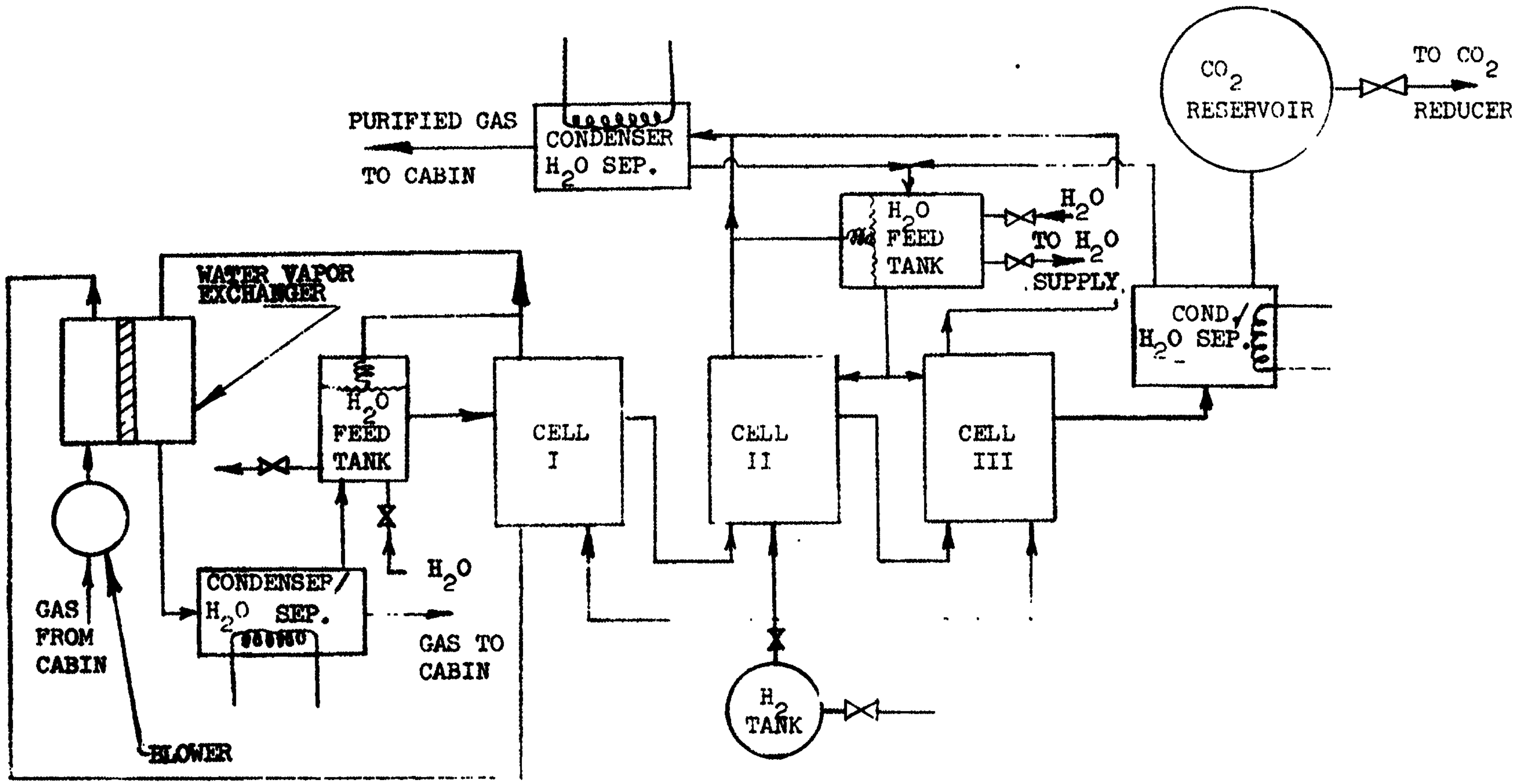


Figure 4-61. Carbonation Cell CO_2 Collector

where it picks up both moisture and heat from the return gas processed in Cell I. The moisture laden atmosphere is routed from the water vapor exchanger to Cell I, where it is stripped of most of its CO_2, and is then returned to the opposite side of the water vapor exchanger. More heat and water are extracted from this return gas in a condenser-water separator before it is routed back to the cabin. Water collected by the water separator is fed into the H_2O feed tank. Further concentration of CO_2 is achieved in Cells II and III. CO_2 can temporarily be stored in the accumulator before its processing in a CO_2 reducer. Some residual hydrogen may be found in the CO_2 concentrate, however, this hydrogen contamination is not detrimental if CO_2 reduction is to be done in a Sabatier or Bosch unit.

Design scaling laws for a carbonation cell CO_2 collector are given in Table 4-52, where $N\bar{w}_c$ is the rate of CO_2 processed in kilograms per day. A detailed breakdown of a 10-man reference unit is shown in Table 4-53. This reference unit is based upon hardware developed by TRW, Inc., but scaled and modified to reflect a unit with hydrogen introduced into the cell anodes (References 4-81 and 4-82). This unit's mass balance is based on a

Table 4-52

DESIGN SCALING LAWS FOR CARBONATION CELL CO_2 COLLECTOR

System Weight = $6.8 + 13.5 (N\bar{w}_c)^{0.85}$ kg

System Volume = $0.0175 (N\bar{w}_c)^{0.795}$ m^3

System Power Requirements = $50 + 4.46 (N\bar{w}_c)$ $watts_e$

Heat Rejection to Air, Q_{RA} = $49.6 + 88.5 (N\bar{w}_c)$ $watts_t$

Hydrogen Requirement = $0.08 (N\bar{w}_c)$ kg

Oxygen Requirement = $0.364 (N\bar{w}_c)$ kg

Water Credit = $0.409 (N\bar{w}_c)$ kg

Table 4-53

DETAILS OF A 10-MAN CARBONATION CELL CO_2 COLLECTOR

Component	Weight* kg (lb)	Power (watts$_e$)	Q_{RA} (watts$_t$)
Cells	68 (150)	220	850
Condenser-water separator (3 req)	8.15 (18)		
Water vapor exchanger	3.62 (8)		
H_2O feed tanks (2 req)	4.53 (10)		
CO_2 reservoir	0.90 (2)		
Blower	1.80 (4)	50	50
Valves, controls and instrumentation	6.80 (15)	50	50
Structural support	13.60 (30)		
TOTAL	107.40 (237)	320	950

*Volume of unit 11.3×10^{-2} m^3

chemical reaction which may be summarized as follows:

$$O_2 + 2H_2 + 2CO_2 \longrightarrow 2H_2O + 2CO_2,$$

where the CO_2 terms represent CO_2 transferred from the cathode to the anode. The unit operates with hydrogen supply richer than stoichiometric. It will consume 0.080 kg of H_2/kg of CO_2 and 0.364 kg of O_2/kg of CO_2. It will produce 0.409 kg of H_2O/kg of CO_2.

4.5.1.6 Molecular Sieves

Regenerative molecular sieve units use granular synthetic zeolites, as the basic CO_2 collecting material. The zeolites are metal ion alumino silicates. The molecular sieve has a relatively high affinity for CO_2, but it has a still higher affinity for water. Thus, desiccants must be used to reduce the moisture content in the cabin atmosphere before it is introduced into the zeolite beds. Desiccant materials used may be either silica gel or another synthetic zeolite. Molecular sieve units usually include air coolers to lower the temperature of the atmosphere being fed to the zeolite canisters to increase the CO_2 adsorption capacity of these beds. Timers are used to actuate valves and to alternate flow between beds. The synthetic zeolites of interest for CO_2 adsorption have a heat of adsorption of 194 watt-hours/kg of CO_2, a specific heat of 0.291 x 10^{-6} $watt_t$-hours/kg °C, a thermal conductivity of 0.0059 watts/cm °C, and a density of approximately 708 kg/m^3.

Three methods of CO_2 removal by molecular sieve materials are considered here. These are all of the regenerative type: (1) a two-bed adiabatic system utilizing two types of sieve material within each bed (one type for H_2O adsorption, one for CO_2 adsorption), (2) a two-bed system similar to the first type but having silica gel as the desiccant, a fluid heat exchanger in the silica gel, and (3) a four-bed system whereby the silica gel and molecular sieve materials are contained in separate beds and in which each bed is provided with integral fluid heat exchangers. The first two methods vent both water and CO_2 to space. The last method provides water recovery and, if desired, CO_2 collection for O_2 recovery. The operating characteristics for each of these methods are discussed in the following paragraphs.

A type I system is shown schematically in Figure 4-62. The system is primarily for a low gas flow rate and having a small pressure drop and high removal efficiency. The molecular sieve beds are provided with a Linde type 13X zeolite for water removal and a Linde type 5A zeolite for CO_2 removal. Electrical heaters are provided for bakeout of the beds should they become "poisoned" with water; otherwise, normal regeneration is to simply vent bed to the space environment.

Type II system utilizes silica gel as a desiccant within each bed. The silica gel bed contains an integral fluid heat exchanger to improve the silica gel water adsorption and desorption characteristics. The molecular sieve portion of the bed also contains electrical heaters to aid adsorption and desorption of the molecular sieve bed if it becomes "poisoned" with water. This system is a low gas flow, small pressure drop, high removal efficiency type. Its operation is shown schematically in Figure 4-63.

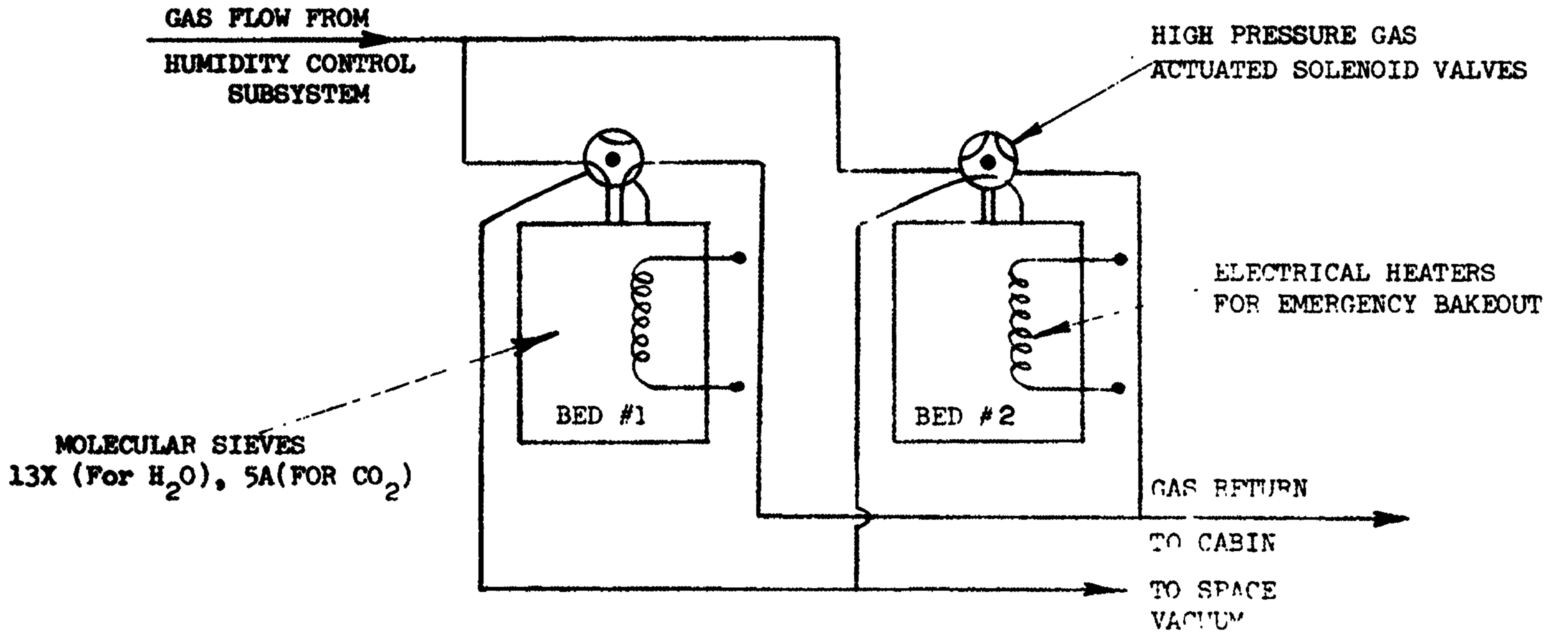


Figure 4-62. Type I Molecular Sieve CO_2 Collector

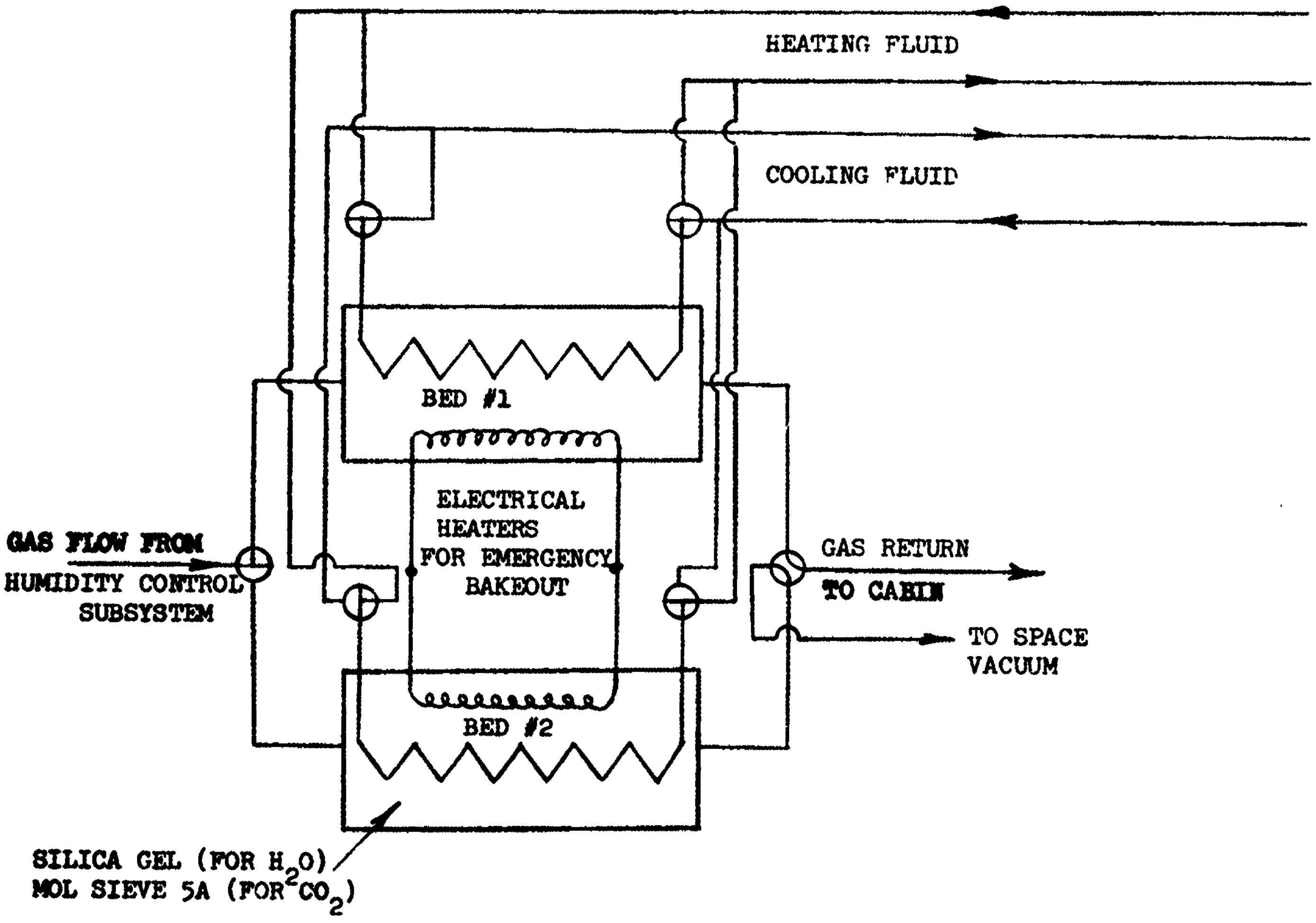


Figure 4-63. Type II Molecular Sieve CO_2 Collector

Type III molecular sieve CO_2 removal unit is the four bed type. In this method, the silica gel and molecular sieve materials are packaged in separate beds. Each bed is provided with an integral heat exchanger to improve adsorption and desorption characteristics. A schematic of the system is shown in Figure 4-64. In the operation mode shown in the schematic, silica gel bed No. 1 and molecular sieve bed No. 1 are being cooled during their adsorption cycle. The gas from molecular sieve bed No. 1 is then passed through silica gel bed No. 2 which is concurrently heated to desorb trapped water and return it to the cabin. At this time, molecular sieve bed No. 2 is being heated and desorbed. The CO_2 may be going to space, or if an oxygen recovery subsystem is used, then pumps are provided to pump the recovered CO_2 into an accumulator or recovery unit. When pumps are used, a higher temperature is required for CO_2 desorption because of the pump limitations.

The design assumptions made in computing the scaling laws for the three types of molecular sieve units are given in Table 4-54. and these are

Table 4-54

MOLECULAR SIEVE CO_2 COLLECTOR DESIGN ASSUMPTIONS

Design Parameters	Type I(1) Collector	Type II(1) Collector	Type III(2) Collector
Inlet gas temperature, °C (°F)	10	11.1	4.44
Inlet dew point, max., °C (°F)	10	11.1	4.44
Length of adsorption or desorption cycles, min.	15	30	30
Cabin CO_2 pressure, mm Hg	5.0	6.5	4.0
Heating fluid temperature, °C (°F)	--	49	149
Cooling fluid temperature, °C (°F)	--	14.4	4.44
Fan overall efficiency, %	35	35	Computed

---

(1) For collectors Type I and II, see Reference 4-84.
(2) For collector Type III, see Reference 4-83.

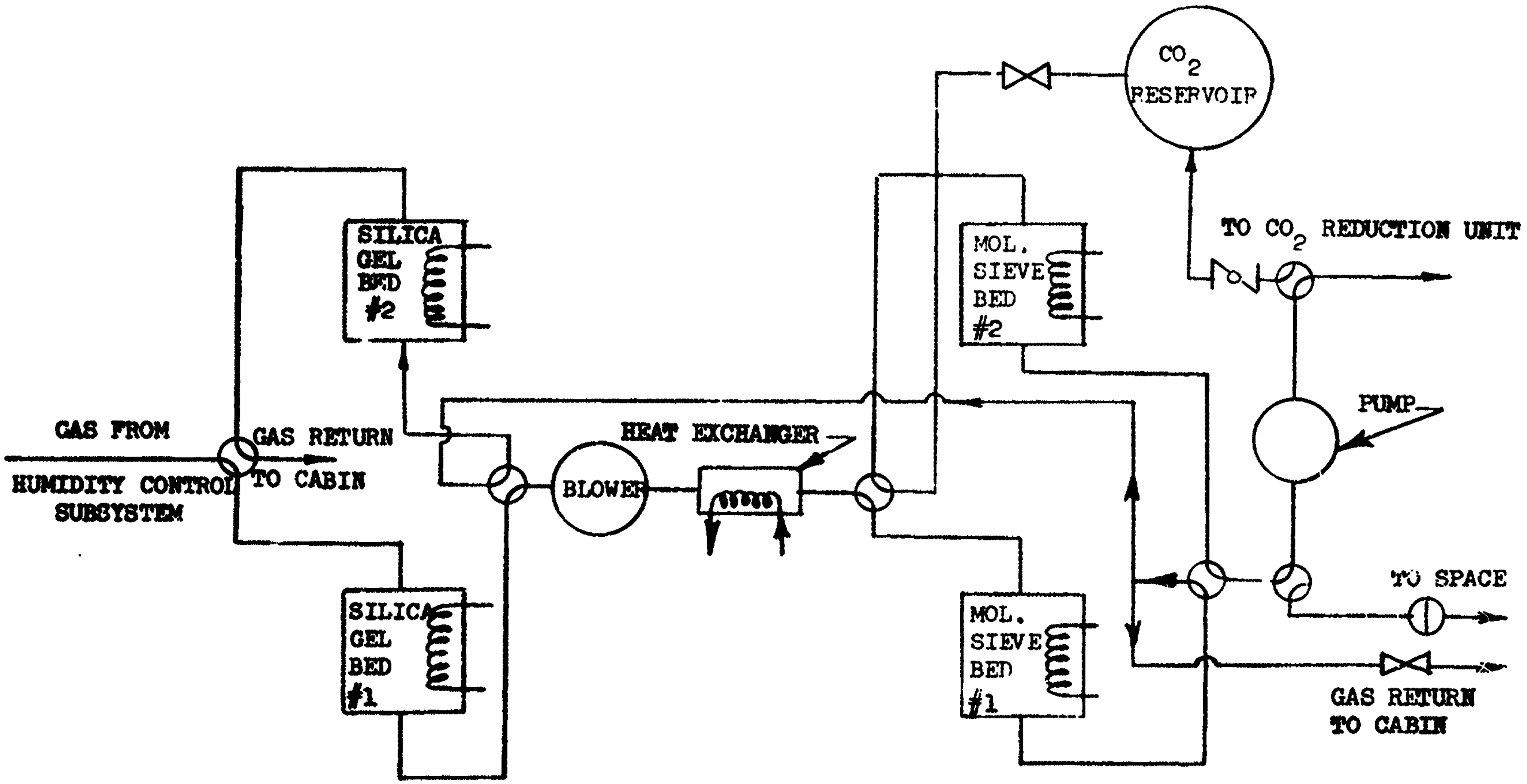


Figure 4-64. Type III Molecular Sieve CO_2 Collector

considered typical and representative. Changes in the design assumptions change somewhat the scaling laws. As an example, a two-fold change in the allowable cabin CO_2 partial pressure may result in nearly a two-fold change in the size of the beds, the heat exchanger and several other important components of the unit. A bakeout of a Type I system is required once each 30 days. A bakeout of Type II or III systems is required once each 45 days.

The design scaling laws for the three types of molecular sieve units are shown in Table 4-55. These units are based on prototype hardware and test data reported in References 4-83 and 4-84.

Table 4-55

DESIGN SCALING LAWS FOR MOLECULAR SIEVE CO_2 COLLECTOR (page 1 of 2)

A. Type I

System Weight = $6.7 + 4.7 (N\bar{w}_c)^{0.5} + 12.63 (N\bar{w}_c)$ kg

System Volume = $8.5 \times 10^{-3} + 0.043 (N\bar{w}_c)$ m^3

System Power Requirement = $(2.85 \rho_g + 0.128) (N\bar{w}_c)$ watts_e

Water Loss = $0.006 p_s (N\bar{w}_c)$ kg/day

Atmosphere Gas Loss = $0.689 \rho_g (N\bar{w}_c)$ kg/day

B. Type II

System Weight = $4.61 + 14.7 (N\bar{w}_c)$ kg

System Volume = $5.65 \times 10^{-3} + 0.038 (N\bar{w}_c)$ m^3

System Power Requirement = $(0.815 \rho_g + 0.075) (N\bar{w}_c)$ watts_e

Water Loss = $0.00635 p_s (N\bar{w}_c)$ kg/day

Atmosphere Gas Loss = $0.23 \rho_g (N\bar{w}_c)$ kg/day

Cooling Requirement = Heating Requirement = $64.8 (N\bar{w}_c)$ watts_t

---

Table 4-55 (page 2 of 2)

C. Type III

(1) When no oxygen recovery system is used in conjunction with system:

$$\text{System Weight} = 4.98 + 10.8\,\rho_g^{0.4}\,(N\bar{w}_c)^{0.4} + 3.54\,(N\bar{w}_c)^{0.5} + 8.54\,(N\bar{w}_c)\ \text{kg}$$

$$\text{System Volume} = 0.052\,(N\bar{w}_c) + 0.0042\,(N\bar{w}_c)^{1.5}\ \text{m}^3$$

$$\text{System Power Requirement} = 37.3\left[\frac{\rho_g\,N\bar{w}_c}{2.54 + 0.8\log\frac{\rho_g\,N\bar{w}_c}{3.75}}\right]\text{watts}_e$$

$$\text{Water Loss} = 0.0097\,(N\bar{w}_c)\ \text{kg/day}$$

$$\text{Atmosphere Gas Loss} = \rho_g\left(0.038\,(N\bar{w}_c) + 1.46 \times 10^{-3}\,(N\bar{w}_c)^{1.5}\right)\text{kg/day}$$

$$\text{Cooling Requirement} = 25\,(N\bar{w}_c)^{0.5} + 178\,(N\bar{w}_c)\ \text{watts}_t$$

$$\text{Heating Requirement} = 25\,(N\bar{w}_c)^{0.5} + 260\,(N\bar{w}_c)\ \text{watts}_t$$

(2) If any oxygen recovery subsystem is used, then a pump and accumulator must be added to the system and the following must be added to the above scaling laws. These are based on a pump efficiency of 0.25 and a 35 psia accumulator pressure.

$$\Delta\text{Weight} = 2.26 + 1.64\,(Nw_c)^{0.24} + 0.81\,(Nw_c)^{2/3} + 0.045\,(Nw_c)\ \text{kg}$$

$$\Delta\text{Volume} = 0.71 \times 10^{-2} + 0.0171\,(N\bar{w}_c)\ \text{m}^3$$

$$\text{Vacuum Pump Power} = 16.1\,(N\bar{w}_c)\ \text{watts}_e$$

Water loss and atmospheric gass loss are eliminated and the above heating and cooling requirements are increased and these laws become:

$$\text{Cooling Requirements} = 38.4\,(N\bar{w}_c)^{0.5} + 243\,(N\bar{w}_c)\ \text{watts}_t$$

$$\text{Heating Requirement} = 38.4\,(N\bar{w}_c)^{0.5} + 325\,(N\bar{w}_c)\ \text{watts}_t$$

4.5.2 Trace Contaminant Removal

Trace contaminant removal equipment removes or controls atmospheric contaminants sufficiently to limit the concentrations to some acceptable level. Contaminants may be separated into the broad categories of particles and gases. Particles include solids such as dust as well as small liquid droplets. Those gases which have been identified as potential contaminants and those which have been detected in the Mercury and Gemini space vehicles, submarines, Apollo outgassing tests, Earth-based space cabin simulator tests are rather extensive. However, at the present time there exist no adequate criteria for predicting outgassing or generation rates for nonbiological contaminants. Reference 4-85 has an extensive discussion of these gases and the measured generation rates have been treated conservatively to establish the required removal rates. These generation rates and maximum allowable concentrations from Reference 4-85 provide the basis for designing and sizing the capacity of the trace contaminant removal equipment. The necessary equipment includes particulate filters, activated charcoal, and catalytic burners. Particulate filters include not only a debris filter but also an absolute filter used in conjunction with charcoal. The debris filter traps coarse particles entering the atmosphere purification loop and the absolute filter removes particles in size down to 0.3μ. Activated charcoal is impregnated with phosphoric acid for removal of ammonia and basic (high pH) compounds, but the activated charcoal is primarily to remove contaminant gases having a high molecular weight. The catalytic burner oxidizes the various lower molecular weight gases in the cabin atmosphere to CO_2, water vapor, or other compounds. Pre- and postsorbent beds are included with the catalytic burner to prevent catalyst poisoning and to remove the undesirable oxidation products. The selected sorbent bed material is usually LiOH. These can be acid-impregnated activated charcoal, Linde type 13 Zeolite, and LiOH sorbents. The LiOH is more desirable for during usage the presorbent LiOH will be partially converted to $LiCO_3$ due to CO_2 absorption. The combination LiOH and $LiCO_3$ presorbent will effectively remove such compounds as SO_2, H_2S, HCl, and HF. As a postsorbent, it will remove such acid gases as HCl and HF resulting from the catalytic oxidation processes.

The activated charcoal and catalytic burner are provided as an option in the atmosphere purification loops, shown in Figure 4-33. Catalytic burners would generally not be used for short missions (such as those for Mercury, Gemini, and Apollo) but they would probably be included in life support systems for future longer missions in which the contaminant levels would have time to build up.

Debris filters are assumed to be included in atmosphere purification loops for all cases. Each unit is assumed to weigh 1 lb (0.5 kg) for all cases (Reference [illegible] 5). The pressure drop is assumed to be 0.2 in. of water. This pressure drop is somewhat greater than 20% of the value assumed for the combined charcoal and absolute filter unit.

The assumed activated charcoal/absolute filter unit characteristics are from Reference 4-85 and are given in Table 4-55. This unit was sized for a nine-man system, and it represents an average size for the range of crew size considered for this study. The unit is unique in that the charcoal bed is designed to provide a reasonable residence time (approximately 0.2 sec) for contaminant removal. The scaling laws for weight of expendable charcoal and absolute filter material also were determined from the estimated expendable requirements in Reference 4-85. These weights were 500 lb of charcoal and 50 lb of absolute filter material for six men on a 2-year mission. The relationships in Table 4-56 assume that expendable weights are linear functions of man-days.

The catalytic burner was parameterized from data presented in Reference 4-85. Table 4-57 contains these reference data. A catalytic burner includes a 0.5% palladium catalytic bed, electrical heaters, and a regenerative heat exchanger all contained within a vacuum insulated jacket. The pre- and post-sorbent bed filters are connected to the catalytic burner with tubing, and the filter canisters and the catalytic burner are assembled on a lightweight structural frame. The gas flow for the reference case was determined on the basis of CO control. Reference 4-85 indicates that a given air velocity is required for control. It appears that trace gas generation

Table 4-56

ACTIVATED CHARCOAL AND ABSOLUTE FILTER UNIT CHARACTERISTICS(*)

WEIGHT	
Charcoal	11.3 kg (25.0 lb)
Absolute Filter	1.1 kg (2.5 lb)
Structure	1.1 kg (2.5 lb)
	13.6 kg (30.0 lb)
SIZE	
Frontal Area	= 0.371 m^2 (4.0 ft^2)
Total Length	= 0.203 m (8.0 in.)
PRESSURE DROP	= 0.14 cm Hg (0.75 in. H_2O)
NOMINAL AIR FLOW	= 6.08 m^3/min (215 cfm)
RESIDENCE TIME	= 0.19 sec
DESIGN SCALING LAWS	

Expendable Charcoal
Weight = 0.0515 x (man-days), kg

Expendable Absolute Filter
Weight = 0.00515 x (man-days), kg

(*)Data from Reference 4-85

rates may be considered to be proportional to crew size so that catalytic burner gas flows may be linearly scaled. The assumptions are used to determine the weight, power, and pressure drop scaling laws given in Table 4-57. According to Reference 4-85 heater power and gas outlet temperatures can be expected to vary by not more than 15% for a cabin atmospheric pressure

Table 4-57

CATALYTIC BURNER ASSEMBLY

Characteristic	Crew Size 9	 6	 3
Weight			
Catalytic burner	12.2 kg (27 lb)	11.4 kg (25 lb)	9.5 kg (21 lb)
Presorbent and canister	14.1 kg (31 lb)		
Postsorbent and canister	11.4 kg (25 lb)		
Structure	1.36 kg (3 lb)		
Volume			
Assembly	0.155 m^3 (5.5 ft^3)		
Catalytic burner	0.0082 m^3 (505 $in.^3$)	0.0074 m^3 (465 $in.^3$)	0.0069 m^3 (423 $in.^3$)
Power	125 $watts_e$	100 $watts_e$	73 $watts_e$
Pressure Drop	0.78 cm Hg (4.2 in. H_2O)	0.428 cm Hg (2.3 in. H_2O)	0.168 cm Hg (0.9 in. H_2O)
Flow	0.0845 m^3/min (3 cfm)	0.0562 m^3/min (2 cfm)	0.0283 m^3/min (1 cfm)
Outlet Temperature	29.2°C (110°F)	29.2°C (110°F)	29.2°C (110°F)

Design Scaling Laws

Catalytic burner weight = $7.55 \times (\text{number of crew})^{0.229}$, kg

Pressure drop = $0.5 \times 10^{-3} + 0.3 \times 10^{-3} \times (\text{number of crew})^{1.61}$, kg/cm^2

Power = $30 + 20 \times (\text{number of crew})^{0.71}$, $watts_e$

$$\textbf{Volume} = \begin{cases} 0.057\ m^3, & \text{total man-days} < 1{,}000 \\ 0.227\ m^3, & \text{total man-days} > 10{,}000 \\ 0.038 + 1.9 \times 10^5 \times (\text{man-days}), & 1{,}000 < \text{man-days} < 10{,}000 \end{cases}$$

(Data from Reference 4-85)

range from 0.35 to 1.029 kg/cm^2 (5 to 14.7 psia). The parameterized weights for presorbent, postsorbent, and structural frame are shown in Figure 4-65.

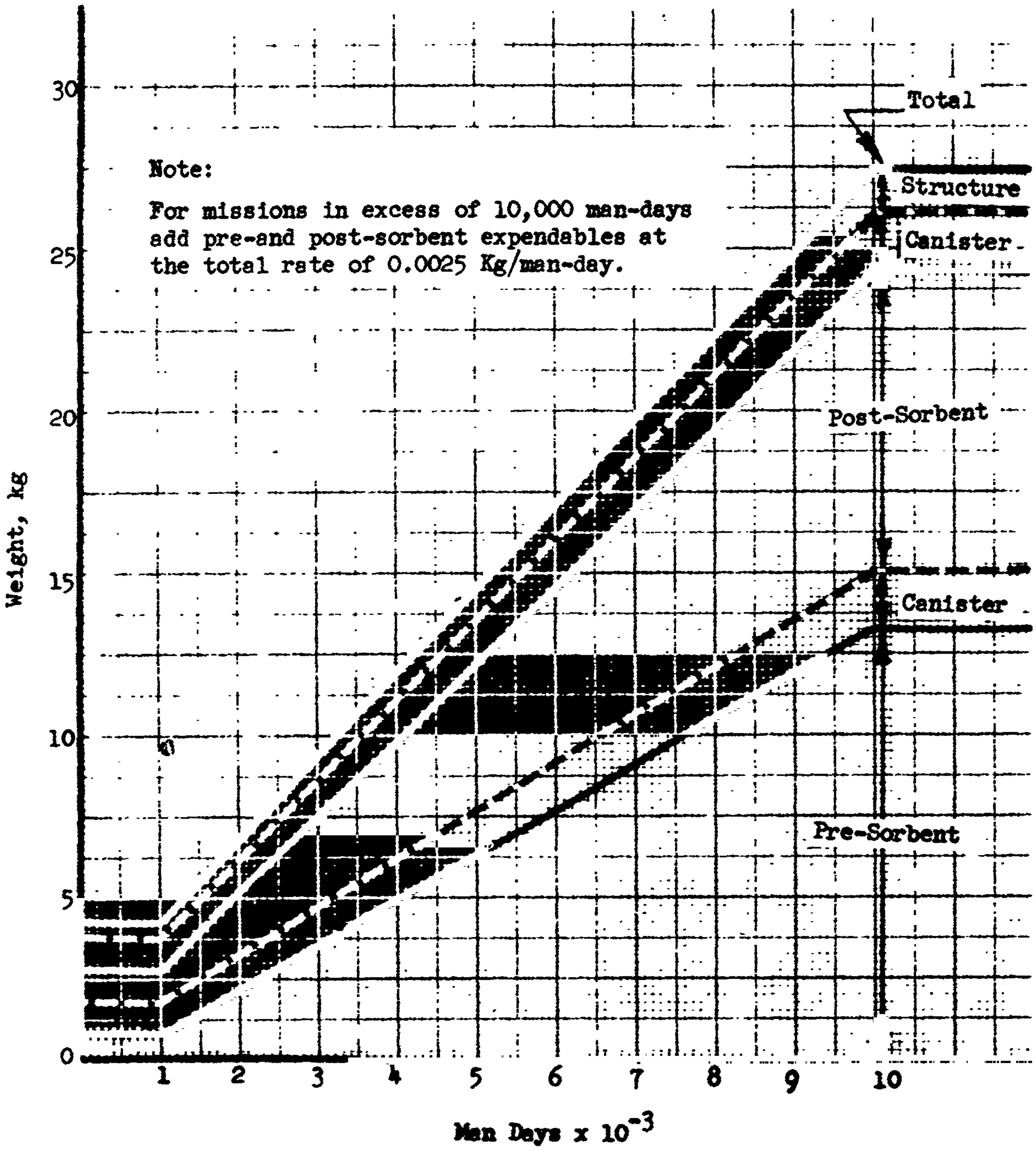
4.5.3 Urine, Feces, and Refuse Management

Urine and fecal wastes generation rates are proportional to the number of crewmen and their diet. Refuse, however, includes all other solid wastes produced by man and the equipment within the spacecraft. Included in this category are such items as emesis, hair, skin, hygenic aids, used wrapping materials and containers, disposable clothing, debris, and solid wastes from other subsystems. These wastes mav be chemically treated, dehydrated, transferred to other reduction systems, stored, or, in the case of urine, dumped overboard. The storage of these wastes may serve as a form of radiation shielding, see Subsection 3.4.

Urine, feces, and refuse are treated as a functional group because they are generally handled partially or wholly within an integrated unit. However, the various candidate management methods for urine, feces, and refuse are distinct and can be and will be discussed separately below. This will enable the engineer to assemble an integrated unit which is compatible with the particular interfaces of the subsystem he has chosen for his mission.

4.5.3.1 Requirements and Constraints

The important design criteria for the equipment are the production rate and specific gravity of the waste materials before and after treatment. Production rates of such waste materials as urine and feces may be computed using data in Subsection 3.3. However, nominal ranges and design values of the major contributors have been assembled and are listed in Table 4-58. Using the design values given in Table 4-58 the scaling laws for the urine, fecal, and refuse management units will generally be functions of the number of men or the number of man-days. There is also another important design requirement: the number of men served by one toilet unit for the integrated toilet units. A commonly suggested value for this parameter is 5 to 6 men



Note:

For missions in excess of 10,000 man-days add pre-and post-sorbent expendables at the total rate of 0.0025 Kg/man-day.

Figure 4-65. Pre-Sorbent, Post-Sorbent and Structure Weights

Table 4-58

DESIGN CRITERIA FOR URINE, FECES, AND REFUSE WASTE MANAGEMENT (page 1 of 3)

Item	Range	Design Value	Reference
Urine			
Volume per micturation, cc	66 - 325	800 - 900	4-86
Volume per man-day, cc/m-d		1500	4-87
	985 - 1835	1835	4-88
Micturation rate, cc/sec		45	4-86 4-89 4-90
Micturations per man-day		6	4-89
Specific gravity	1.002 - 1.035		4-91
Feces			
Mass per defecation, gm	50 - 250	160	4-92
Volume per defecation, cc (normal)		300	4-90
Mass per man-day, gm/m-d		150	4-89
(low residue diet)		227	4-87
Defecations per man-day		1.00 - 1.14	4-93
Specific gravity		1.0	4-86
Fecal water, mass percentage		76	4-89
		67	4-87
Emesis			
Volume per man-day, cc/m-d	230 - 900		4-94
Debris			
Mass per man-day, gm/m-d		238	4-88
Volume per man-day (after drying), cc/m-d		20	4-90

Table 4-58 (page 2 of 3)

Item	Range	Design Value	Reference
Urine collection bags (semi-permeable)			
Mass, gm		4	4-95
Emesis/debris bags (semi-permeable)			
Mass, gm		4	4-95
Number required per man day		0.50	4-93
Personal urinal sealing diaphragms			
Mass, gm		4	4-95
Number required per mission day		0.6	4-95
Cleaning package for use after waste eliminations			
Skin cleanser, gm/m-d		3	4-95
Skin wipes, gm/m-d		18	4-95
Storage bags for solid wastes (impermeable to gas and liquid), mass, gm			
Feces			
Emesis/debris		2.	4-95
Specific gravity		1.85	4-94
Wet pack body cleaning package (12 small pads - 2 wet, 2 large pads - 1 wet)			
Mass per man-day, gm/m-d		160	4-94
Specific gravity		0.37	4-94

Table 4-58 (page 3 of 3)

Item	Range	Design Value	Reference
Miscellaneous wastes			
Food tubes			
Mass per man-day, gm/m-d		77	4-87
Bags and paper			
Mass per man-day, gm/m-d		73	4-87
Sanitary tissue (noseblowing, tearing, etc.)			
Mass per man-day, gm/m-d		4	4-94
*Expendable items for urine, feces, and emesis disposal (includes collection bags, wipes, and germicides)			
Mass per man-day, gm/m-d		91 43 78	4-92 4-93 4-95
Fecal collection bags (semi-permeable)			
Mass, gm		4	4-95
Specific gravity		0.52	4-94
Toilet tissues			
Mass, gm/defecation			
(gm/m-d)		21	4-95
Specific gravity		0.20	4-94
Germicide			
Mass per defecation, % of feces		2 - 4	4-86

***For these systems, urine was generally collected in bags and vacuum distilled, therefore the bags are considered as solid wastes.**

per toilet unit. Therefore, it was assumed for this study that the system designer would provide a separate integrated urine, fecal, and debris unit for every 5- to 6-man increment in crew size.

4.5.3.2 Urine Management Methods

Three urine collection devices are considered. All missions must provide a pressure suit urine collection device which will be worn during launch, re-entry, and EVA periods. This device can also serve as an emergency backup unit during normal space flight operations. The pressure suit unit consists of a Y-shaped bag which fits inside the spacesuit around the pelvic region. A fitted sleeve is provided on one side for insertion of the penis and the opposite side provides a valved hose extension which is used to empty the bag into the urine processing equipment. The scaling laws for this unit are as follows:

$$\text{Weight} = 205 \times (\text{no. of men}),\ \text{gm} \qquad (4\text{-}152)$$

$$\text{Volume} = 360 \times (\text{no. of men}),\ \text{cc} \qquad (4\text{-}153)$$

For normal space flight operations, the collection units are: (1) the personal urine bag, (2) the overboard vented urinal, and (3) the air entrainment urinal with associated blower and water separator. The third method may be connected to an overboard vent system or to an accumulator transfer device for further processing, and each unit is discussed in detail below.

The personal urine bag is similar to that used in the Gemini flights. It consists of a sleeve type penis receptacle, a sleeve connector, shutoff valve, urine sample valve, a collection bag, and connection for the urine transfer unit. In developing the scaling laws for this unit the following assumptions were made:

1. A germicide dispenser will be provided for chemically treating the urine and disinfecting the bag. Two grams of germicide will be injected into the bag following each micturation.
2. A disposable penis receptacle will be replaced every day.

3. The main collection bag will be replaced every 30 days. The scaling laws for the personal urine bag follow:

$$\text{Weight} = 100 + 260\,(\text{no. of men}) + \left[2.0 + 2.0\,(\text{micturations/m-d}) + \frac{80}{30}\right] \times (\text{m-d})\ \text{gm} \qquad (4\text{-}154)$$

$$\text{Volume} = 400 + 255\,(\text{no. of men}) + \left[16. + 2.0\,(\text{micturations/m-d}) + \frac{65}{30}\right] \times (\text{m-d})\ \text{cc} \qquad (4\text{-}155)$$

where m-d indicates the number of man-days involved, and the last terms in each equation are truncated integers representing replacement of urine bags on 30-day intervals.

The overboard vent urinal is similar to that used on the Apollo spacecraft. It consists of a cone shaped urinal, provided with a combination sealing cap and holder assembly and a urinal transfer hose with a quick disconnect fitting. This is shown schematically in Figure 4-66. This urine collection unit is used with an overboard vent system described later. The urine stream is entrained in cabin gas and both are vented overboard. An orifice in the vent line limits the amount of gas or urine flow out of the dump line. It is estimated that an orifice sized for a urine maximum flow rate of 45 cc/sec will result in a cabin gas loss of approximately 2 cfm of 5 psia O_2. Data taken from References 4-92 and 4-93 were used to develop the following scaling laws which assume that a germicide spray dispenser is provided, and that 1 ml of germicide is sprayed into the urinal after every micturation.

$$\text{Weight} = 470 + 1.0\,(\text{micturation/m-d})\,(\text{m-d})\ \text{gm} \qquad (4\text{-}156)$$

$$\text{Volume} = 820 + 1.0\,(\text{micturations/m-d})\,(\text{m-d})\ \text{cc} \qquad (4\text{-}157)$$

The third method of urine collection utilizes the same type air entrainment urinal and transfer tube described in the second method but it also includes a blower, filter, and urine-gas separator. This system is shown schematically in Figure 4-67. This type of collection unit will generally be used

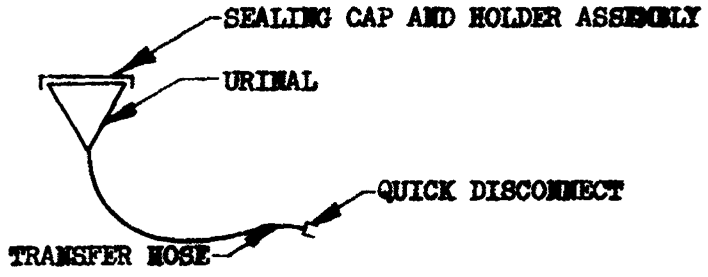


Figure 4-66. Overboard Vent Urinal

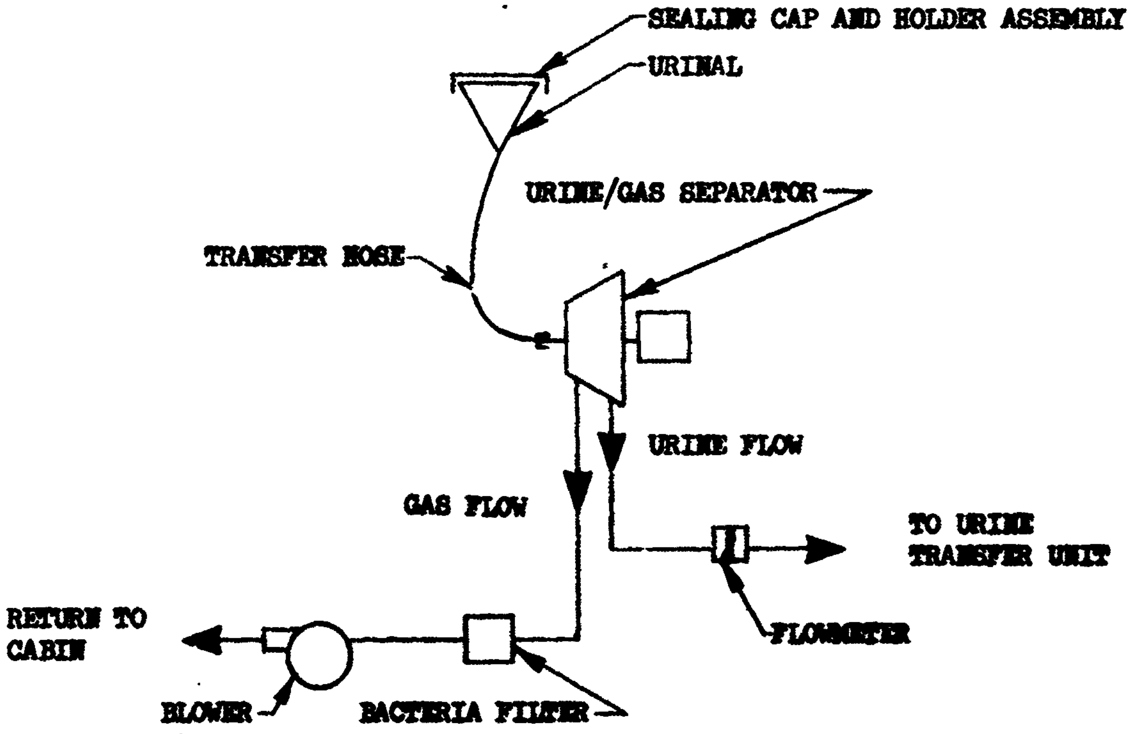


Figure 4-67. Air Entrainment Urinal with Urine/Gas Separator

for the longer duration missions; therefore a turbine flowmeter with an estimated weight of 910 gm has been included to measure individual urine quantities (Reference 4-89). This is important in the medical monitoring of the crew to determine possible dehydration of the crewmen during long-term missions. Data from References 4-89, 4-92, and 4-95 as well as the same assumptions for the previously described units were used in developing the following scaling laws:

$$\text{Weight} = 4970 + 1.0\,(\text{micturations/m-d}) \times (\text{m-d})\ \text{gm} \qquad (4\text{-}158)$$

$$\text{Volume} = 4825 + 1.0\,(\text{micturations/m-d}) \times (\text{m-d})\ \text{cc} \qquad (4\text{-}159)$$

$$\text{Power} = 42\ \text{watt}_e \qquad (4\text{-}160)$$

The urine collection units are connected to some type of a transfer device. Two transfer devices were considered: (1) the overboard dump system and (2) the bladder tank accumulator which is used in conjunction with urine storage or water recovery systems. The overboard dump unit consists of a hose connector, bacteria filter, dump valve, transfer line, and heated orifice. It is shown schematically in Figure 4-68. Using data from Apollo and References 4-92 and 4-94 and assuming a transfer line of 20 ft of 3/8-in. diameter stainless steel tube, the following scaling laws were developed:

$$\text{Weight} = 1{,}995\ \text{gm} \qquad (4\text{-}161)$$

$$\text{Volume} = 1{,}390\ \text{cc} \qquad (4\text{-}162)$$

$$\text{Power} = 5.7\ \text{watt} \qquad (4\text{-}163)$$

The bladder tank accumulator and transfer device is shown schematically in Figure 4-69. The unit consists of a bladder tank, used for intermediate storage, chemical treatment, and transfer of urine; a three-way valve for directing urine flow; required system connections; and if desired, a germicide dispenser and storage tank. The latter unit may not be required if

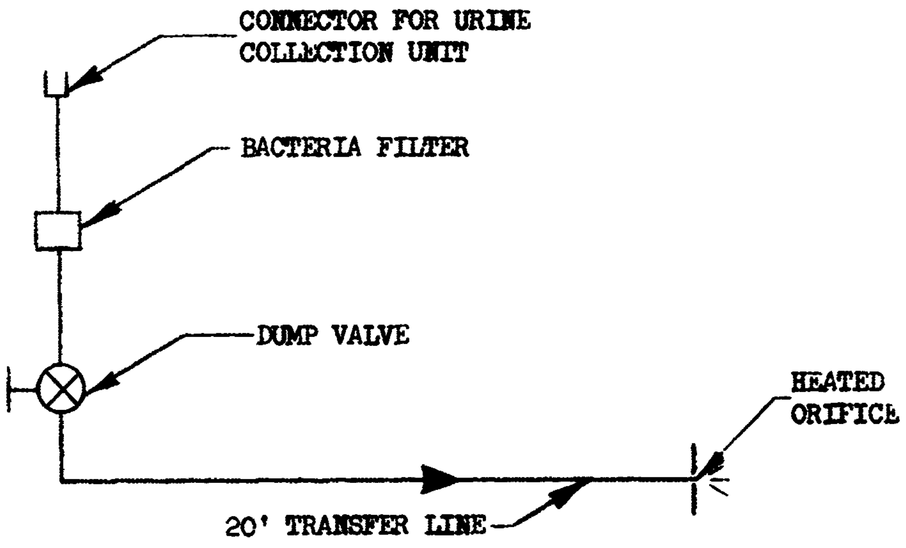


Figure 4-68. Urine Overboard Dump Transfer Device

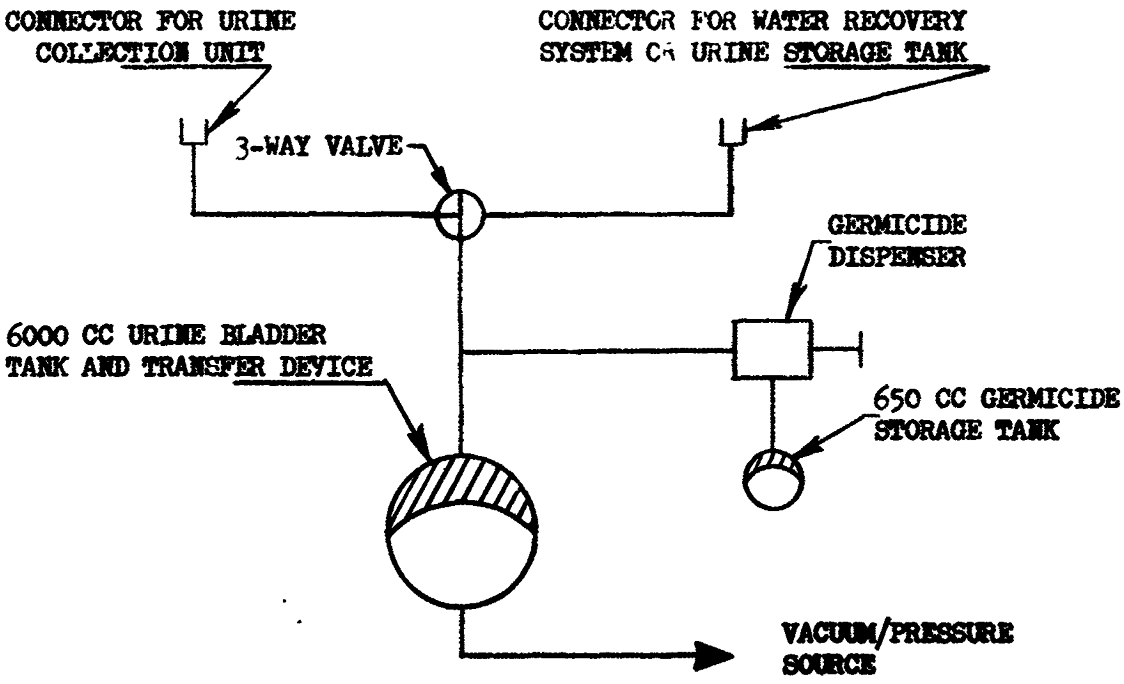


Figure 4-69. Urine Bladder Tank and Transfer Device

germicide treatment was provided in the urine collection unit; therefore, the germicide treatment unit effect will be delineated in the following scaling laws, which were developed using data from References 4-89 and 4-90 and assuming a 2 gm germicide treatment for each micturation.

$$\text{Weight} \quad 2405 + \left[1160 + 2\,(\text{micturations/m-d}) \times (\text{m-d})\right] \qquad (4\text{-}164)$$

$$\text{Volume} = 7470 + \left[1015 + 2\,(\text{micturations/m-d}) \times (\text{m-d})\right] \qquad (4\text{-}165)$$

where the terms in brackets are for the germicide treatment unit.

If treated urine is to be stored in storage tanks, a good estimate of required spherical tank weight appears to be equal to approximately 10% of the urine weight to be stored. Volume requirements are approximately 101% of the urine volume. The following scaling laws for urine storage tanks were developed using the assumptions that the average urine volume per man day = 1,500 cc, and the specific gravity of urine = 1.019:

$$\text{Weight} = 154.5 \times (\text{m-d})\ \text{gm} \qquad (4\text{-}166)$$

$$\text{Volume} = 1515 \times (\text{m-d})\ \text{cc} \qquad (4\text{-}167)$$

4.5.3.3 Fecal Management

Three methods of feces collection and processing will be discussed. These are (1) manual bagging and storage using chemical treatment; (2) air entrainment into semipermeable bags followed by vacuum drying and storage; and (3) air entrainment of feces and formation of a water/feces slurry which can be pumped to a fecal water recovery system or a biological waste treatment system.

Manual Bagging

The manual bagging technique was used on Gemini flights and is acceptable and applicable for short-duration missions and emergency use. This technique utilizes a laminated plastic bag with an adhesive coated circular

opening at one end for attachment to the person. A germicide pouch and tissue wipes are included with each bag. The pouch is inserted into the bag prior to body attachment. Following defecation the bag is removed, used tissues are inserted, the bag is sealed, and the germicide pouch is ruptured and mixed with the feces by kneading the bag. The treated feces may then be stored. The following scaling laws account for the collection and storage bag combination, the germicide, and the tissue wipes.

$$\text{Weight} = 90 \times (\text{m-d}) \text{ gm} \qquad (4\text{-}168)$$

$$\text{Volume} = 100 \times (\text{m-d}) \text{ cc} \qquad (4\text{-}169)$$

The scaling laws for storage container, weight and volume requirements for the manual bagging technique include the following assumptions:

1. Storage containers will weigh approximately 10% of the feces weight (Reference 4-97) and will occupy approximately 110% of the combined feces and bag volume
2. Fecal material assumptions:
   a. defecations per man day = 1.0
   b. mass per defecation = 150 gm
   c. specific gravity = 1.0

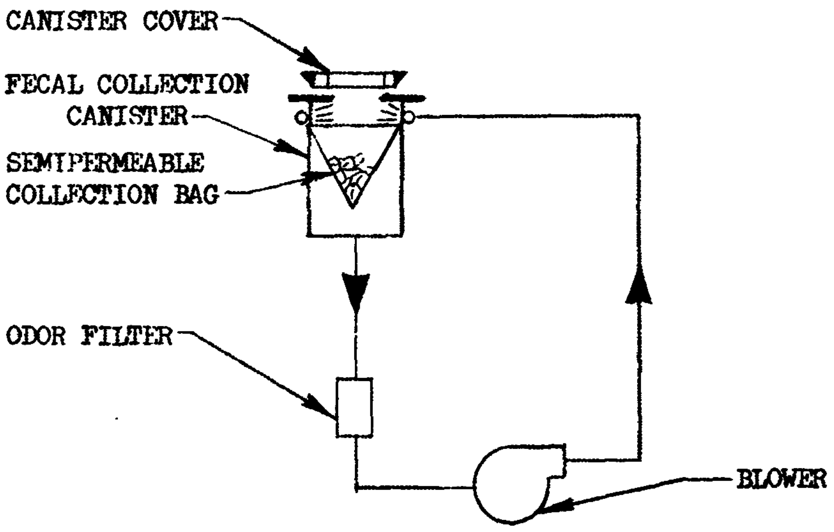
The manual bagging design scaling laws are as follows:

$$\text{Weight} = 15.0 \times (\text{m-d}) \text{ gm} \qquad (4\text{-}170)$$

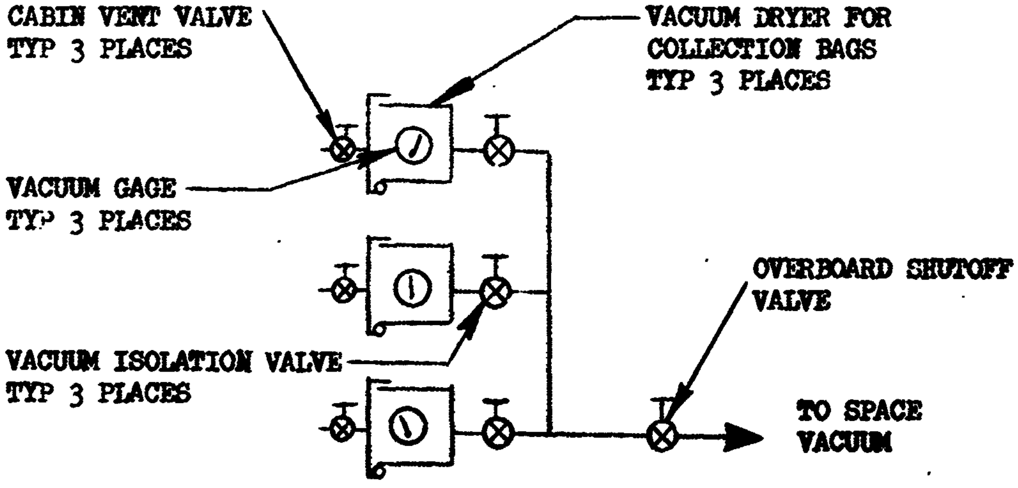
$$\text{Volume} = 275.0 \times (\text{m-d}) \text{ cc} \qquad (4\text{-}171)$$

Air Entrainment with Vacuum Drying

The second method of fecal management utilizes air entrainment and vacuum drying of feces, and it is shown schematically in Figure 4-70. The unit consists of a fecal collection canister and cover coupled with an odor filter. A blower provides gas flow for separation, transfer, and containment of the feces. Nozzles located within the fecal canister toilet seat direct gas flow toward the anal area of the crewman. Feces are separated, transported,



Air Entrainment Loop



Fecal Vacuum Drying Components

Figure 4-70. Fecal Management System

and kept in the semipermeable collection bag by the gas flow returning to the blower. Following defecation and disposition of toilet tissues the crewman seals the collection bag, manually transports it to a vacuum dryer, the fecal canister is covered, and the blower stopped. The vacuum dryer compartment is actuated by opening the vacuum isolation valve. Heat leakage from the cabin provides the necessary heat for evaporation of the fecal water. After a sufficient drying time, the vacuum isolation valve is closed, the cabin vent valve is opened to repressurize the dryer compartment, and the dried fecal matter is removed, placed in an impermeable storage bag, and stored. This same unit and procedure may also be used for emesis collection when used with a suitable collector and adapter.

This method of feces management is applicable for missions in which no attempt is made at fecal water recovery. Reference 4-78 indicates that if 50 to 60% of the fecal water can be removed, then the remaining wastes can be stored without chemical treatment for about 75 days. The waste heat dryer characterized in Reference 4-92 was capable of obtaining 50% water removal within 18 to 24 hours. Data from the dryer of Reference 4-92 and the following assumptions were used in developing the scaling laws for this unit:

1. One defecation per man-day
2. Provision for 1 dryer per man plus 1 for contingency
3. A 21% weight increase of the basic components was allowed for structure and a 150% volume increase was allowed for packaging, Reference 4-89.

$$\text{Weight} = 1.21[5510 + 1020\,(\text{no. of men})] + 51 \times (\text{m-d})\ \text{gm} \qquad (4\text{-}172)$$

$$\text{Volume} = 2.5[13770 + 1480\,(\text{no. of men})] + 75 \times (\text{m-d})\ \text{cc} \qquad (4\text{-}173)$$

$$\text{Power} = 35\ \text{watt}_e \qquad (4\text{-}174)$$

The storage container characteristics are based on the following assumptions:

1. **Storage containers will weigh approximately 10% of the feces weight and occupy approximately 100% of the wet feces volume (Reference 4-87).**

2. Fecal material
    - A. Defecations per man day = 1.0
    - B. Mass per defecation = 150 gm
    - C. Specific gravity = 1.0
    - D. Water content = 75%
3. Sixty percent of the fecal water will be removed

Following are the design scaling laws for the storage container:

$$\text{Weight} = 8.25 \times (\text{m-d}) \text{ gm} \tag{4-175}$$

$$\text{Volume} = 150 \times (\text{m-d}) \text{ cc} \tag{4-176}$$

Air Entrainment with Slurry Formation

The final method of fecal management that will be discussed provides for air entrainment of feces followed by a water wash of the crewman and commode and the formation of a fecal slurry. The equipment required for this method is shown schematically in Figure 4-71. As in the previous method, feces are separated by jets of recirculated gas and transferred into a collector. The collector consists of a water/feces blender and gas separator. The gas is pumped from the collector and returned to the cabin via a bleed orifice to maintain a negative pressure in the fecal receptacle. Following defecation, flush water from an electrically heated accumulator is directed first at the crewman's anal area, and during the second flush, downward into the commode. The wash water is air entrained the same as the feces. The water/feces blender and gas separator mixes the feces and flush water to form a slurry. During feces blending, the gas duct valve is repositioned so all gases from the separator are routed to the odor filter and cabin air is drawn into an air heater and directed toward the anal area to provide drying of the crewman. When defecation is complete and feces have been slurried, the slurry is pumped through a flowmeter and into a fecal slurry accumulator where it may be temporarily stored prior to

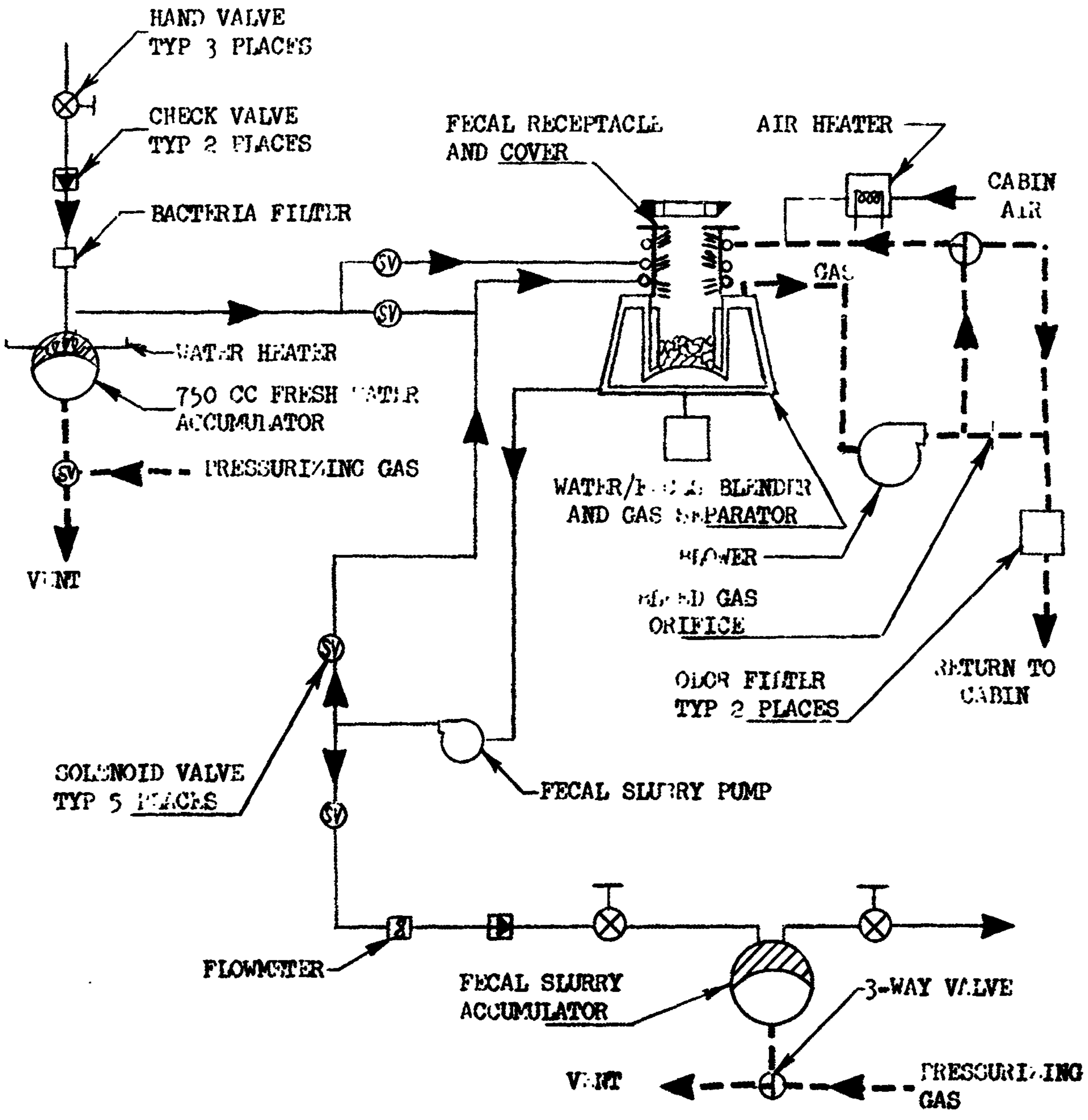


Figure 4-71. Waste Management System

processing. The scaling laws were developed for this equipment using data from Reference 4-89 together with the following set of assumptions:

1. Fecal Material
    - A. defecations per man day = 1.0
    - B. mass per defecation = 150 gm
    - C. specific gravity = 1.0
2. A 150% volume increase was allowed for packaging

The design scaling laws for the air entrainment with slurry formation follow.

$$\text{Weight} = 21100 + 630 \times (\text{no. of men})\ \text{gm} \qquad (4\text{-}177)$$

$$\text{Volume} = 2.5\left[28850 + 1560 \times (\text{no. of men})\right]\text{cc} \qquad (4\text{-}178)$$

$$\text{Power} = 76.2\ (\text{during use}) + 0.65 \times (\text{no. of men})\ (\text{continuous})\ \text{watts}_e \qquad (4\text{-}179)$$

$$\text{Flush water required} = 1500\ \text{cc/m-d} \qquad (4\text{-}180)$$

$$\text{Fecal slurry produced} = 1650\ \text{cc/m-d} \qquad (4\text{-}181)$$

4.5.3.4 Refuse Management Methods

Refuse would generally be stored in impermeable bags. It ordinarily would be collected manually. An air entrainment collector or a portable vacuum cleaner could also be used for debris collection. Emesis could be collected in these devices or in the fecal collectors. The scaling laws for the impermeable storage bags were based on data from Reference 4-92 and include the following assumptions:

1. The amount of refuse produced is equal to the amount of feces produced, which is assumed to be 150 gm/m-d (Reference 4-88).
2. Refuse specific gravity = 1.0

The impermeable storage bags design scaling laws are as follows:

$$\text{Weight} = 25 \times (m-d)\ \text{gm} \tag{4-182}$$

$$\text{Volume} = 42 \times (m-d)\ \text{cc} \tag{4-183}$$

Storage containers were assumed to weigh 10% of the refuse weight, occupy 110% of the combined refuse and bag volume, and have the following design scaling laws:

$$\text{Weight} = 15.0 \times (m-d)\ \text{gm} \tag{4-184}$$

$$\text{Volume} = 210 \times (m-d)\ \text{cc} \tag{4-185}$$

All debris or refuse may also be handled by use of an air entrainment device. The first type is one in which a debris bag receptacle is integrated with an air entrainment fecal collector. A schematic of this device is shown in Figure 4-72. The combination adapter head and cover is provided for

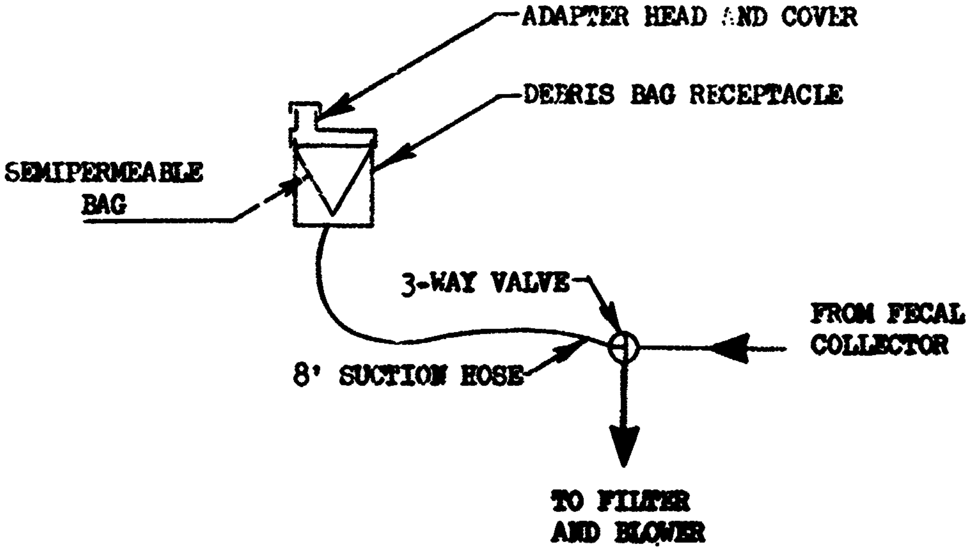


Figure 4-72. Air Entrainment Debris Bag Receptacle

normal debris collection. This may be removed to provide for emesis or large volume debris containment. The scaling laws for this unit were developed from References 4-89, 4-93, and 4-95, and Apollo design data and include the following assumptions:

1. Number of debris bags required = 0.33 bags/m-d
2. Debris collection bags are assumed to be identical to the air entrainment fecal collection bags.
3. The collected debris will be stored in the impermeable bags discussed above.

The design scaling laws for the air entrainment debris bag are as follows:

$$\text{Weight} = 800 + 7\ (\text{m-d})\ \text{gm} \qquad (4\text{-}186)$$

$$\text{Volume} = 4750 + 14\ (\text{m-d})\ \text{cc} \qquad (4\text{-}187)$$

Another type of debris collection device is a self contained portable vacuum cleaner provided with an adapter head which holds the permeable replaceable bag. The capacity assumptions are the same for both types of debris collectors. The scaling laws for the vacuum cleaner type follow.

$$\text{Weight} = 1,800 + 7\ (\text{m-d})\ \text{gm} \qquad (4\text{-}188)$$

$$\text{Volume} = 5,500 + 14\ (\text{m-d})\ \text{cc} \qquad (4\text{-}189)$$

$$\text{Power} = 18\ \text{watts}_e \qquad (4\text{-}190)$$

4.6 FOOD SUPPLY SUBSYSTEM

The food supply subsystem provides for the supply, storage, preparation and in some instances the manufacture of food. The scaling laws were developed for both stored and processed food. The food composition, nutritional requirements and weight used are discussed in detail in Section 3.

4.6.1 Stored Food

A great amount of the stored food technology has been developed and evolved from the Mercury, Gemini, and Apollo programs. Since their design criteria dictate minimum amounts of weight, volume, and preparation, precooked dehydrated foods have been favored. It has been found to be most practical to use dehydrated food and add the necessary water prior to consumption. The water can be later possibly reclaimed from metabolic wastes, processed, and reused. The food management system consists of a stack of storage canisters, each of which may be judicially sized to contain 1/2 to 1 day supply of food, depending on the size of the crew. Individual servings are packaged in flexible, lightweight containers which can accommodate liquids as well as bite-size pieces. Each food item container serves as storage vessel and may serve as the food preparation utensil and zero-gravity eating device. Included also would be individual trays, trayholders, pullout seats, heat exchangers for heating and cooling the reconstitution water, the associated water dispensers, and necessary utensils and flatware. Included also are serving trays, napkins, cleaning pads, and storage drawers, as well as the holding brackets and structural support for the equipment. It has been assumed that in preparing beverages and reconstituted foods, one-half of the intake water will require heating while the other half will require chilling.

Design scaling laws, based on size of crew and weight of food per crew member each day, $(N\bar{w}_{sf})$ kg of stored food served per day (see Subsection 3.3) are given in Table 4-59 for a crew of N men, a mission duration of t days, a water intake of $\bar{w}_{H_2O}$ kg/day.

4.6.2 Processed Food

Fully closed life support systems, may be characterized primarily by the closure of the food-waste loop. Ecological closure is achieved by processing crew metabolic wastes to form some form of synthetic or natural food. Both chemical synthesis and biological regeneration methods are considered. Glycerol, D-fructose, and ethanol have been suggested as being the most promising of chemical food synthesis compounds. The glycerol process has been taken as being representative of these three methods and is discussed in detail below and its design scaling laws have been derived and presented. Previous studies indicated that formaldehyde synthesis as an intermediate step is the most feasible route for the synthesis of carbohydrates.

Table 4-59

DESIGN SCALING LAWS FOR STORED FOOD MANAGEMENT FACILITIES

System Weight = $1.1\ N\bar{w}_{sf}\ t + 0.276\ Nt + 7.95N$, kg

System Volume* = $0.0424N + 0.0069\ N\bar{w}_{sf}\ t$, m^3

System Power Requirement = 2N watts_e (continuous)

Cooling Load, $Q_{Rc} = 9.7\ N\bar{w}_{H_2O}\ \text{watts}_t$ 15 - min. duty,

Heating Load = $35.6\ N\bar{w}_{H_2O}\ \text{watts}_t$ 4 times daily

---

*The system volumetric requirements are given for equipment volume only, no allowance for seating is included.

This approach was used in the studied glycerol process (Reference 4-97). Glycerol feeding experiments have been conducted on both human and animal subjects (References 4-98, 4-99, and 4-100). Conclusions made are that glycerol can be used safely to supply 1/3 to 1/2 of the required daily diet. The remainder may be supplied either as stored food or some other processed food, probably Hydrogenomonas.

Biological systems are the other avenue for closing the food-waste loop. Two types of biochemical reactions are being considered for regenerative life support systems. The first is photosynthesis, in which process cell materials are synthesized from CO_2 and H_2O by living plant cells, using a visible light as an energy source. Leading photosynthetic organisms under consideration for life support systems are algae, including chlorella, synechococcus, scenedesmus, and anacystis, and several types of vascular plants such as duckweed, lettuce, endive, chinese cabbage, and sugar cane. The second is biochemical reaction in which the electrolysis of water to produce oxygen is combined with the chemical synthetic reduction of CO_2 by such hydrogen-fixing bacteria as Hydrogenomonas. The Hydrogenomonas proccss has been selected as representative and probably the most promising of the biological processes. A detailed description of the process, its mass balances, and design scaling laws are presented below.

4.6.2.1 Glycerol Process

The glycerol process is a four-step chemical reaction which uses hydrogen and metabolic CO_2 to synthesize, in order, methanol, formaldehyde, trioses, and glycerol. Table 4-60 presents a summary of the processes involved, catalysts used, reaction chamber conditions and operational criteria. Estimated process yields are also included. Reference 4-101 gives a more detailed and thorough discussion of these processes. A simplified glycerol process schematic is shown in Figure 4-73. The solid electrolyte oxygen recovery unit is used to reduce CO_2 to CO and oxygen. Carbon monoxide together with hydrogen from the system water electrolysis system are delivered to the methanol reactor. The formaldehyde, trioses, and glycerol reactors follow. The solid wastes from the four reactors, in addition to the fecal and urine solids from the waste management and water recovery units, are oxidized in the incinerator to H_2O, CO_2, and carbon. A mass balance of the glycerol process is presented in Table 4-61 per unit mass of carbon dioxide. This is a typical case based upon an average crew size, activity level, and diet.

Design scaling laws for the glycerol process unit are presented in Table 4-62, where $(N\bar{w}_c)$ is the rate of CO_2 processed in kg per day. These laws were developed largely from the chemical reactions involved and making engineering designs of the equipment required. There have been no flight hardware items assembled for such a unit; however, several analytical designs have been made of the processes (References 4-101 through 4-106).

Table 4-63 gives a detailed breakdown of the analytical engineering design for a 10-man unit based upon the mass balances of Table 4-61.

4.6.2.2 Hydrogenomonas Process

The unique feature of the Hydrogenomonas process is the ability of the Hydrogenomonas bacteria culture to assimilate in a hydrogen rich environment carbon dioxide and urine as the sources of hydrogen, carbon, oxygen, and nitrogen required for growth. Fecal material is oxidized in an incinerator to CO_2 and H_2O, and these products are also supplied to the culture.

Table 4-60
GLYCEROL SYNTHESIS SYSTEM CHARACTERISTICS

Reaction	Catalyst	Conditions	Yield	Operational Criteria	Reference
Methanol	Mixed Zn, Cr, Mn oxides	T = 300°C P = 300 atm	90-95% (15% per pass)	Multistage compressor to pressurize CO, H_2. Reaction chamber followed by condenser/separator. Wastes to incinerator and Methanol liquid reduced to 1 atm.	4-102, 4-103
Formaldehyde	Ag and Cu screens	T = 635°C P = 1 atm	85-90% (65% per pass)	Heated methanol and air to reaction chamber. Formaldehyde/methanol solution is condensed in absorber. Wastes to incinerator. Formaldehyde is separated in a fractionating column.	4-102, 4-104, and 4-105
Trioses	Na_2SO_3 (solution)	T = 50°C (1 hr) P = 1 atm	74%	Water solution of formaldehyde is heated with Na_2SO_3.	4-106
Glycerol	Black platinum (H_2 in ethanol solution)	T = 25°C P = 1 atm (0.5 hr)	90-95%	Mixture from reaction chamber to rectification column. Wastes to incinerator. Glycerol filtered and withdrawn.	4-101

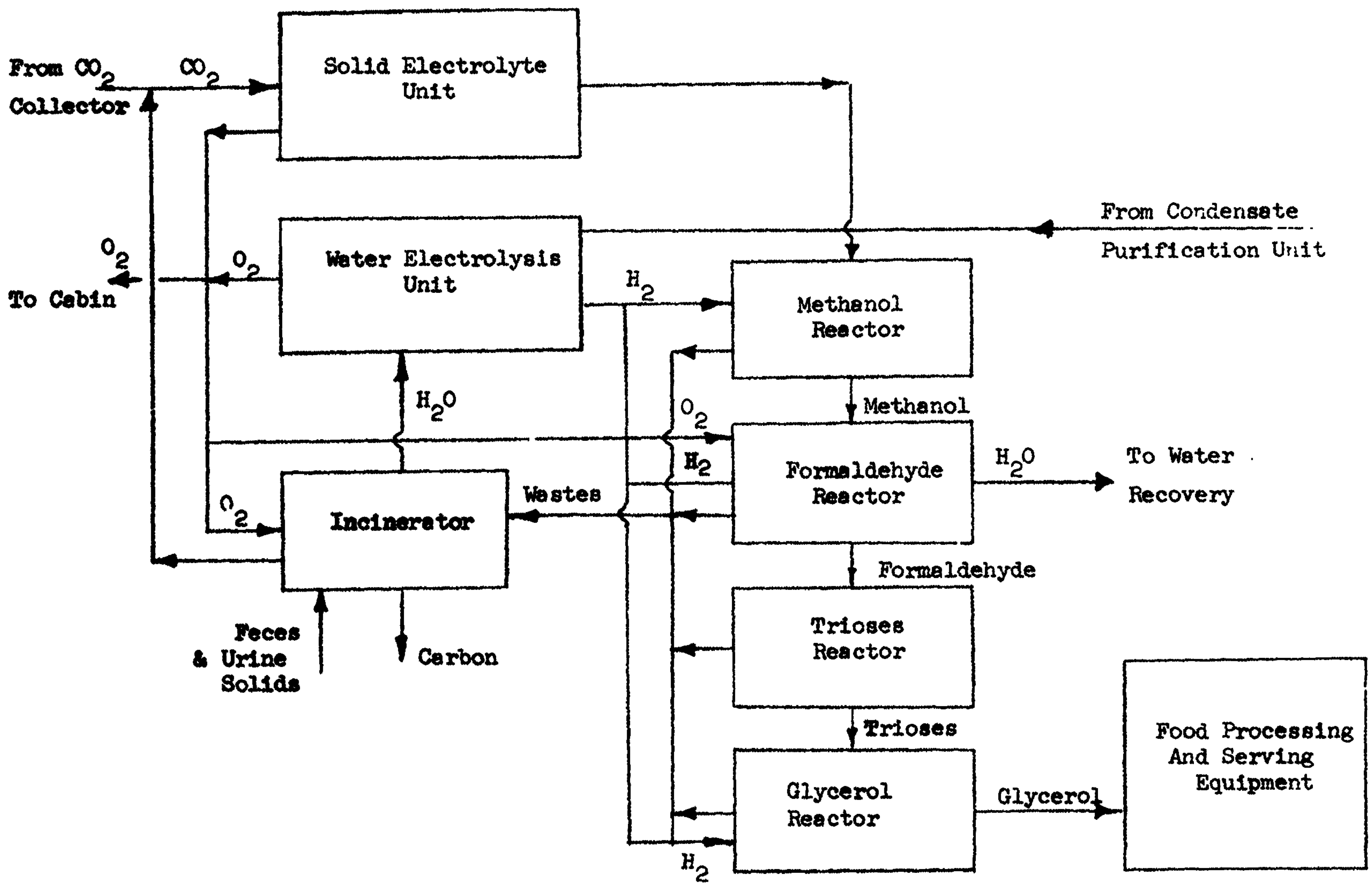


Figure 4-73. Glycerol Processing System Flow Schematic

Table 4-61

MASS BALANCE OF GLYCEROL PROCESS

Input (unit mass/ unit mass of CO_2)		Output (unit mass/ unit mass of CO_2)	
Carbon dioxide	1.000	Oxygen	0.856
Liquid water	0.510	Water vapor	0.216
Feces solids	0.168	Carbon	0.101
Urine solids	0.12	Glycerol	0.625
TOTAL	1.798	TOTAL	1.798

Table 4-62

DESIGN SCALING LAWS FOR GLYCEROL SYSTEM

System Weight = $24.1 + 38.41\,(N\bar{w}_c) + 14.2\,(N\bar{w}_c)^{0.5} + 23.8\,(N\bar{w}_c)^{0.66}$, kg

System Volume = $1.01\,(N\bar{w}_c)\ m^3$

System Power = $70 + 741\,(N\bar{w}_c) + 899\,(N\bar{w}_c)^{0.745}$ watts_e

Atmosphere Cooling Load, $Q_{RA} = 50 + 151\,(N\bar{w}_c) + 899\,(N\bar{w}_c)^{0.745}$ watts_t

Coolant Cooling Load, $Q_{RC} = 1330\,(N\bar{w}_c)$ watts_t

System Heating Requirement = $738\,(N\bar{w}_c)$ watts_t

The major products of the Hydrogenomonas culture are bacterial cells and water. In a closed ecological system the cellular material is used for food, while the oxygen, electrolyzed from water, is used for breathing.

The reaction performed by Hydrogenomonas is given by the equation:

$$6H_2 + 2O_2 + CO_2 \xrightarrow{\text{(Hydrogenomonas)}} (CH_2O) + 5H_2O \qquad (4\text{-}191)$$

Table 4-63

DETAILS OF A TYPICAL 10-MAN GLYCEROL PROCESSING UNIT

Component	Weight* kg	(lb)	Power (watts$_e$)	Heating (watts$_t$)	Q_{RA} (watts$_t$)	Q_{RC} (watts$_t$)
Methanol reactor, instrumented	104	(230)	5,000	150	500	4,640
Formaldehyde reactor, instrumented	22.6	(50)	20	548	56.8	511
Triosis reactor, instrumented	9.05	(20)	20	100	12	107
Glycerol reactor, instrumented	72.5	(160)	20	6,680	668	6,050
Incinerator	90.5	(200)	1,000	-	100	906
Water electrolysis unit	56.8	(125)	1,520	-	151	1,360
Solid electrolyte unit	131	(290)	5,050	-	5,050	-
Processing and serving equipment	45.3	(100)	50	-	49.60	-
Structural support, piping and controls	45.3	(100)	50	-	49.60	-
TOTAL	577.05	(1,275)	12,730	7,478	653.7	13,574

*Total unit volume = 7.08 m^3 (250 ft^3)

where (CH_2O) represents the cell material. Hydrogenomonas also requires nitrogen for growth. If urine is added to the culture, Hydrogenomonas was found to be capable of utilizing the urea as a sole source of nitrogen. In contrast to photosynthetic systems, the Hydrogenomonas does not require light for growth, but instead it obtains its energy from the recombination of hydrogen and oxygen. When used as food, this cellular material is oxidized with metabolic oxygen to the usual human reaction products.

A schematic diagram of a Hydrogenomonas system is shown in Figure 4-74. Hydrogen, oxygen, CO_2, and urine are supplied under pressure to the mixing chamber. A ratio of $H_2 : O_2 : CO_2 :: 1 : 5.17 : 3.53$ provides a mixture 4-6% richer in hydrogen than stoichiomeric in the mixing chamber. These gas ratios are maintained by controlling the flow of gases with partial pressure sensors. A paddle-type mixer continuously agitates the culture and gases. No apparent need for phase separation arrangements is anticipated. Safety precautions must be taken, however, for oxygen and hydrogen are in the explosive ratio range. Some Hydrogenomonas culture is continuously delivered to a centrifugal solid-liquid separator in which the culture is harvested and delivered to the food processing unit while the excess water is routed to the Hydrogenomonas system water distillation unit. The nutrient makeup is to maintain the proper bacteria-chemical ratios. Solid residues from the distillation unit and feces from the Waste Management Subsystem are oxidized in the incinerator to CO_2, solid carbon, and water. Oxygen is required by the incinerator at the rate of 0.23 kg per kilogram of waste.

The electrolysis unit electrolyzes all the water the distillation unit puts out, and requires some additional water from the vehicle's water purification unit. The excess oxygen over that required by the mixing unit is delivered to the cabin. Table 4-64 gives the mass balance involved in the Hydrogenomonas process, per unit mass of carbon dioxide for an average crew size, activity level and diet. The product culture is delivered mixed in with the output water.

Design scaling laws for a Hydrogenomonas unit are shown in Table 4-65 where Nw_c is the CO_2 processed in pounds per day. A detailed breakdown of a typical 10-man unit is given in Table 4-66. These laws were developed largely from the chemical reactions involved and making engineering designs of the equipment required. There have been no flight hardware items assembled for such a unit; however, several analytical designs have been made of the processes (References 4-101 through 4-106).

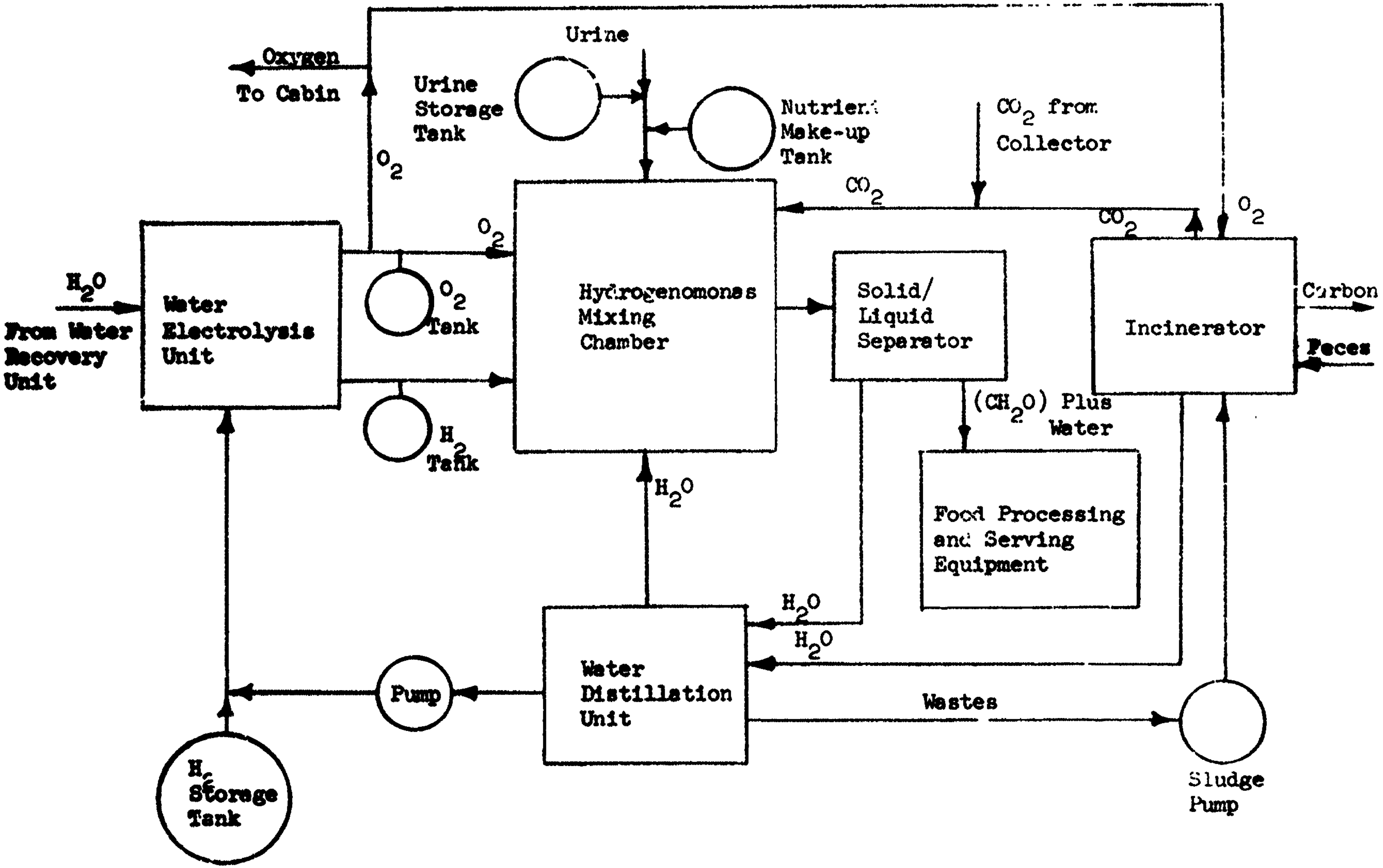


Figure 4-74. Hydrogenomanas Processing Unit Schematic

Table 4-64

MASS BALANCE OF HYDROGENOMONAS PROCESS

Input (unit mass/ unit mass of CO_2)		Output (unit mass/ unit mass of CO_2)	
Carbon dioxide	1.000	(CH_2O) Culture	0.610
Feces	0.164	Oxygen	0.355
Urine	1.500	Water	1.7575
H_2O	0.582	Carbon	0.0235
TOTAL	3.246	TOTAL	3.246

Table 4-65

DESIGN SCALING LAWS FOR HYDROGENOMONAS UNIT

System Weight $= 14.2\ (N\bar{w}_c)^{0} + 4.81\ (N\bar{w}_c)^{0.67} + 68.45\ (N\bar{w}_c)$ kg

System Volume $= 0.313\ (N\bar{w}_c)^{0.948}\ m^3$

System Power Requirement $= 50 + 589\ (N\bar{w}_c)\ \text{watts}_e$

Atmosphere Cooling Load, $Q_{RA} = 50 + 182.8\ (N\bar{w}_c)\ \text{watts}_t$

Coolant Cooling Load, $Q_{RC} = 351\ (N\bar{w}_c)^{0.948}\ \text{watts}_t$

4.7 CREW AND CREW SUPPORT SUBSYSTEM

The crew and crew support subsystem considers the crew, their personal equipment, and those other items which have a direct relationship to the crew. Included are clothing and protective garments for both IVA and EVA along with related support equipment, as well as those systems and equipment which are directly concerned with crew safety.

Table 4-66

DETAILS OF A TYPICAL 10-MAN HYDROGENOMONAS PROCESSING UNIT

Component	Weight* kg(lb)		Power (watts$_e$)	Q_{RA} (watts$_t$)	Q_{RC} (watts$_t$)
Mixing chamber, instrumented, with initial culture	349	(770)	800	796	-
Solid-liquid separator and motor	45.3	(100)	500	499	-
Storage and holding tanks (5 req)	22.6	(50)	-	-	-
Water distillation unit	36.1	(80)	100	100	-
Electrolysis unit	154	(340)	4,150	413	3,720
Incinerator	68	(150)	400	400	-
Processing and serving equipment	45.3	(100)	50	49.6	-
Structural supports, piping and controls	45.3	(100)	50	49.6	-
TOTAL	765.6	(1,690)	6,050	2,307.20	3,720

---

*Total Unit Volume = 2.83 m^3 (100 ft^3)

4.7.1 Requirements and Constraints

The major requirement is to insure effective operation and full capability of each crew member by providing the personal equipment and other items discussed in the following sections to assure adequate support for the crew. Performance parameters of these items need to be integrated with other spacecraft systems to ensure effective man-system integration. Sizing of these requirements for a given mission is dependent largely on the size of the crew and other crew-related characteristics which were discussed earlier in Section 3. Such variables as size of crew, skill levels and types, body sizes, and nutritional requirements will constrain the selection of the items discussed in the following sections.

4.7.2 Space Suits and Clothing

Pressure suits are used in manned space vehicles to maintain a viable environment for the crewman in the event of a cabin depressurization or during extravehicular operation. Due to the uncertainty of cabin decompression, early space vehicles such as Mercury and Gemini were designed to have the crewman in space suits during the entire mission. The Apollo departed somewhat from continuous pressure suit operation, and during some mission phases the crewmen are in shirtsleeves. Longer duration missions currently planned will be designed to have the crewmen in shirtsleeves for the major portion of the mission, that is nonsuited operation, with provisions for short durations in pressure suited operation. Generally, pressure suited operation is not compatible with larger long-range vehicles due to the high penalties incurred in pressure suit ventilation and due to the hardship on the crew wearing pressure suits continuously. Space suit requirements as related to several life support systems are given in Table 4-67 (Reference 4-107). Current space suits are of the "soft" suit design where most of the suit area is pliable fabric. This type of construction results in lighter weight and moderate mobility. The suit has relatively good comfort qualities when the suit is unpressurized as it has somewhat similar characteristics to winter clothing. When pressurized, the suit balloons and thus requires numerous constraint and equalization straps to retain satisfactory mobility and shape. The constraint straps or harnesses hinder movement in both the pressurized and unpressurized state and are uncomfortable. "Hard" space suits currently are under development for use in future space missions. Hard suits will be needed most in planetary surface operations where meteoroid hazard is greatest. Hard suits are designed on the suit of armor principle using fiber glass and aluminum honeycomb panels (References 4-108 and 4-109). The suit parts are at the center of the torso to allow easy donning. Gas distribution is similar to the soft suit

Table 4-67

SPACE SUIT REQUIREMENTS

	Open	Partially Closed	Fully Closed
Suit function	Emergency and EVA	IVA, EVA, in-space experiments and maintenance	IVA, EVA, in-space experiments and maintenance, and planetary operations
Portable life support system (PLSS) capacity	4 hours	8-10 hours	18-24 hours
Umbilical capability	Required	Required	Required
Pressurization	0.26 kg/cm^2 suit 0.36-0.47 kg/cm^2 cabin	0.21-0.49 kg/cm^2 suit 0.35-0.49 kg/cm^2 cabin	0.26-0.528 kg/cm^2 suit 0.49-1.04 kg/cm^2 cabin
PLSS functions:			
CO_2 removal	LiOH or regenerative	LiOH or regenerative	LiOH or regenerative
Thermal control	Water boiler	Water boiler or radiator	Water boiler or radiator
Metabolic heat loads	293 watts inside cabin 350-586 watts outside cabin	Same	Same
Waste management	Urine collection and feces disposal in unpressurized mode, 72-hour retention in emergency mode	Same	Same

concept wherein distribution ducts direct gas flow to the extremities. The vent gas then flows back adjacent to the crewman's skin, thereby providing the required cooling or ventilation. "Hybrid" suits, that is, with hard torsos and soft legs are being developed for a higher internal pressure (0.352 kg/cm^2, abs).

In addition to space suits, the crew will require shirtsleeve type clothing for a major portion of the missions. Descriptions of soft and hard space suits and shirtsleeve clothing are given in Table 4-68.in terms of weights and volumes. No power is required for these items. The scaling laws developed from these characteristics, and incorporating Apollo and Litton suit data, are given in Table 4-69. The scaling laws are applicable to short duration missions, which may not require hard suits, as well as long duration missions which may call for the use of hard suits. The use of a dummy variable in the scaling laws obviated the need for a separate set of laws for each of the two types of missions considered.

4.7.3 EVA Support

This section includes all of those items necessary to support EVA by one or more crewmen, these include portable environmental control systems, bioinstrumentation, maneuvering units, and other supporting equipment such as lights, sun shades, and tools (References 4-110, 4-111, 4-112, 4-113, 4-114). Items included and their characteristics are presented in Table 4-70. Table 4-71 gives the scaling laws for the EVA support equipment for one crewman.

4.7.4 First Aid and Medical Supplies

Items which should be included in first aid and medical supplies are listed in Table 4-72 (References 4-115 and 4-116). Weight, volume, and power requirement of the equipment listed are also indicated. In parameterizing these supplies, they were first divided into two categories: one covering a crew of less than 10 men and the other for a crew of more than 10. It became apparent that the differences between these two categories was small, and thus, the scaling laws were developed as a function of mission duration only and independent of the size of the crew.

Table 4-68

DESCRIPTION OF SPACE SUITS AND CLOTHING

Item	Unit Characteristics	
	Weight [kg (lb)]	Volume [m^3 (ft^3)]
1. Apollo Pressure Suit Assembly		
Integrated Pressure Garment	27.63 (61)	0.241 (8.6)
Spare Suit	27.63 (61)	0.241 (8.6)
O_2 Bottle (with spare suit)	2.26 (5)	0.003 (0.1)
Portable Life Support System	28.99 (64)	0.084 (3.0)
Medical Biovest Assembly	1.36 (3)	0.006 (0.2)
2. Litton Hard Suit Assembly		
Hard Suit	29.45 (65)	0.238 (8.5)
PLSS	29.45 (65)	0.098 (3.5)
Thermal Meteoroid Garment	6.80 (15)	0.028 (1.0)
3. Constant Wear Garment	0.91 (2)	0.003 (0.1)
4. Stockings	0.09 (0.2)	0.001 (0.05)
5. Underwear	0.09 (0.2)	0.001 (0.05)
6. Footwear (IVA)	0.14 (0.3)	0.005 (0.17)
7. Work Coveralls	0.91 (2)	0.003 (0.1)
8. Protective Hat	0.45 (1)	0.008 (0.3)

The scaling laws for the first aid and medical supplies are shown in Table 4-73. Dummy variables were used in the scaling laws to obviate the need for separate sets of laws for each of mission types and equipment utilization assumptions considered. The dummy variable K reflects the fact that X-ray units are used for missions in excess of 3 years in duration. The dummy variables, λ and z, on the other hand, indicate that two simple physical conditioning devices are used for missions of up to 1 year in duration, and three such devices are used for longer duration missions.

Table 4-69
SCALING LAWS FOR SPACE SUITS AND CLOTHING

Weight $= 1.8ND + 96.5N + 197K$ kg

Volume $= N(0.084D + 0.627) + 1.1K\ m^3$

D = mission duration in years

N = number of crew members

K = A dummy variable $= 0$ when $D < 1$
$= 1$ when $D \geqq 1$

Table 4-70
DESCRIPTION OF EVA SUPPORT EQUIPMENT

	Unit Characteristics		
Component Description	Weight, kg (lb)	Volume, m^3 (ft^3)	Power, watts$_e$
Maneuvering unit			
Jet shoes unit	0.91 (2)	0.014 (0.5)	
Tank assembly	44.39 (98)	0.098 (3.5)	
Umbilicals	14.95 (33)	0.084 (3)	
Restraint equipment	2.94 (6.5)	0.006 (0.2)	
Suit-mounted lights	0.68 (1.5)	0.003 (0.1)	
Illumination equipment	4.53 (10)	0.028 (1.0)	18
Handtool kits, tools and tool tethers	8.15 (18)	0.017 (0.6)	
Restraint devices	4.53 (10)	0.056 (2.0)	
Crew monitoring	27.18 (60)	0.031 (1.1)	86
Television monitor	9.06 (20)	0.011 (0.4)	20
Camera	5.44 (12)	0.003 (0.1)	12
Receiver	0.91 (2)	0.003 (0.1)	4
Recorder	11.78 (26)	0.014 (0.5)	50

---

*Items included in scaling laws of Table 4-71.

Table 4-71

DESIGN SCALING LAWS FOR REQUIRED EVA SUPPORT EQUIPMENT FOR ONE CREW MAN

Weight = $21D + 578$ kg for $1 < D \leq 5$
Weight = $437D + 163$ kg for $0 \leq D \leq 1$

Volume = $0.07D + 2.14$ m^3 for $1 < D \leq 5$
Volume = $1.58D + 0.63$ m^3 for $0 \leq D \leq 1$

Power = $86D + 280$ watts_e for $1 < D \leq 5$
Power = $254D + 112$ watts_e for $0 \leq D \leq 1$

D = mission duration in years

Table 4-72

DESCRIPTION OF FIRST AID AND MEDICAL SUPPLIES

	Unit Characteristics		
Equipment Description	Weight, kg (lb)	Volume, m^3 (ft^3)	Power, watts_e
1. First Aid Kit	13.59 (30)	0.028 (1)	-
2. Medication, dressing material, splints and casting material, minor surgical instruments, utensil sterilization unit	45.3 (100)	2.1 (75)	100
3. X-Ray unit (includes its own power supply - two 12-volt batteries)	45.3 (100)	0.210 (7.5)	-
4. Simple physical conditioning devices, e.g. bungee cord, etc.	9.06 (20)	0.014 (0.5)	-
5. Simple training aids of minor level for life support system and personnel operation and maintenance.	22.65 (50)	0.042 (1.5)	-

Table 4-73

DESIGN SCALING LAWS FOR FIRST AID AND MEDICAL SUPPLIES

Weight $= 41D + 45K + 18\lambda + 27Z + 60$ kg

Volume $= 1.615D + 0.21K + 0.02\lambda + 0.03Z + 1.13$ m^3

Power $= 75D + 50$ watts_e

D = mission duration in years

K = A dummy variable $= 0$ for $D < 3$
$= 1$ for $D \geq 3$

λ = A dummy variable $= 0$ for $D > 1$
$= 1$ for $D \leq 1$

Z = A dummy variable $= 0$ for $D \leq 1$
$= 1$ for $D > 1$

4.7.5 Personal Items and Hygiene Kit

The items listed in Table 4-74 are considered to be required by each crew member. The weight, volume, and power requirements for each item are listed (Reference 4-117). Some of the items such as hair clippers, razors, towels, etc., would be excluded for missions of less than 30 days in duration. The scaling laws for the personal items and hygiene kits are given in Table 4-75, and they include all the items listed in Table 4-74 for missions of more than 30 days (1/12 year).

4.7.6 Instrumentation and Controls

The instrumentation and controls in the Crew Support Subsystem are those dealing with data management and data storage of information in regard to the crew's well being, medical condition, and operation of the life support equipment (Reference 4-118). This equipment is largely dependent upon the mission duration and is relatively independent of the number of the crew. Descriptions of the items included in this category are given in Table 4-76 and these include weight, volume, and power requirements. Table 4-77

Table 4-74

DESCRIPTION OF PERSONAL ITEMS AND HYGIENE KIT

Item Description	Unit Characteristics Weight, kg (lb)	Volume, m^3 (ft^3)	Power $watts_e$
Razor	0.45 (1)	0.003 (0.1)	1
Hair clippers (set includes redundant clippers)	1.36 (3)	0.003 (0.1)	1
Nail clippers, file, etc. set	0.23 (0.5)	0.003 (0.1)	--
Toilet Soap (one bar per 30 man-days)	0.23 (0.5)	0.003 (0.1)	--
Bath Soap (one Prell concentrate for 30 baths)	0.14 (0.3)	0.003 (0.1)	--
Towels (a package of 4 for each crewman)	1.81 (4)	0.008 (0.3)	--
Handkerchiefs (a dozen per crewman)	0.45 (1)	0.003 (0.1)	--
Toothpaste (one tube per 60 man-days)	0.23 (0.5)	0.003 (0.1)	--
Comb and brush per crewman	0.23 (0.5)	0.003 (0.1)	--
Personal photos, momentos	1.36 (3)	0.003 (0.1)	--
Pocket books, records/tapes	2.27 (5)	0.006 (0.2)	--
Miscellaneous, (thread and needle, pins, etc.)	0.23 (0.5)	0.003 (0.1)	--
Dry wipes (package of 480 for 60 man-day supply)	5.57 (12.3)	0.011 (0.4)	--
General purpose tissues - 240/box	0.14 (0.3)	0.003 (0.1)	--

Table 4-75

DESIGN SCALING LAWS FOR PERSONAL ITEMS AND HYGIENE KIT

$\text{Weight} = 0.23N + (1.4 + 6.43N + 4.716ND)\,K + 0.666NZ$ kg

$\text{Volume} = 0.00283N + (0.00283 + 0.2762N + 0.02366ND)\,K + 0.00163NZ$ kg

$\text{Power} = 2\,NK$ watts

N = Number of crew members

D = Mission duration in years

$$K = \text{A dummy variable} = 0 \text{ when } D < 1/12$$
$$= 1 \text{ when } D \geq 1/12$$

$$Z = \text{A dummy variable} = 1 \text{ when } D \leq 1/12$$
$$= 0 \text{ when } D > 1/12$$

---

presents the scaling laws used in computing this class of equipment. Assumptions made for the utilization of data management and storage equipment included the following:

1. For mission durations of less than a week, a portable recording unit is carried onboard for data storage, and no data management equipment is used.
2. Data storage facilities for interplanetary flights, in excess of 3-years duration, are influenced by the fact that most of the data will be stored only while the spacecraft is in the vicinity of the target planet. Data storage facilities for such interplanetary missions were found to require approximately 60% of the equipment needed for a 1-year surveillance type Earth orbital space station.

The dummy variables, K, z, λ, and γ, used in developing the crew support subsystem instrumentation and controls scaling laws, made it possible for one set of laws to depict equipment which meets all of the above assumptions.

4.8 CREW ACCOMMODATIONS SUBSYSTEM

The crew accommodations subsystem is concerned with the various functional facilities or areas of the spacecraft in which the crewmen live.

Table 4-76

DESCRIPTION OF CREW SUPPORT SUBSYSTEM INSTRUMENTATION AND CONTROLS

	Unit Description		
Equipment Description	Weight, kg (lb)	Volume, m^3 (ft^3)	Power $watts_e$
Data Management System			
Data acquisition units (2)	13.59 (30)	0.014 (0.5)	30
Digital processor and controller	27.18 (60)	0.028 (1.0)	160
Data conditioning unit	12.23 (27)	0.008 (0.3)	14
Down link buffer	10.42 (23)	0.006 (0.2)	10
Control center	9.06 (20)	0.034 (1.2)	100
Data Storage			
Digital recorders (2)	90.6 (200)	0.071 (2.5)	170
Video bandwidth recorders (2)	54.36 (120)	0.040 (1.4)	150
Wide bandwidth analog recorders (2)	90.6 (200)	0.068 (2.4)	170
Portable recording systems:	43.04 (95)	0.020 (0.7)	115
Two record systems			
Two reproduce systems			
Two battery packs			
Six electronic modules			
40 tape cartridges			

Table 4-77

DESIGN SCALING LAWS FOR CREW SUPPORT SUBSYSTEM INSTRUMENTATION AND CONTROLS

Weight $= (70 + 279\gamma) K + 38\lambda + 161Z$ kg

Volume $= (0.096 + 0.2\gamma) K + 0.02\lambda + 0.09Z$ m^3

Power $= (314 + 605\gamma) K + 100.0\lambda + 360.0Z$ watts_e

D = Mission duration in years

K = A dummy variable $= 0$ for $D \leq 1/52$
$= 1$ for $D > 1/52$

Z = A dummy variable $= 0$ for $D < 3$
$= 1$ for $D \geq 3$

λ = A dummy variable $= 0$ for $D > 1/52$
$= 1$ for $D \leq 1/52$

γ = A dummy variable $= 0$ for $D > 3$
$= 1$ for $D \leq 3$

Included are considerations relevant to accommodations or equipment for personal hygiene, food management, sleeping, and other related areas which may be important for some missions.

4.8.1 Requirements and Constraints

The major requirement is to provide the living and recreational spaces necessary for the accomplishment of mission objectives, and to have the spacecraft interior layout such that these spaces are effectively utilized, and to provide suitable accommodations for the necessary crew functions.

4.8.2 Living and Recreational Facilities

The facilities considered under this category include major items such as the sleeping station, the shower, and the laundry facilities. Included also are small items such as locations and numbers of the oxygen masks to be at critical points throughout the spacecraft. The recreational facilities deal with such activities as doing calisthenics, reading books, preparing a personal diary, listening to tapes, and playing competitive games with fellow astronauts (Reference 4-119). The facilities and equipment involved in these activities have been included in the parametric relations for various other portions of Subsection 4.7 and, therefore, are not included in the parametric relations for this portion of Subsection 4.8. However, the discussion of recreational requirements is included here with the discussions of work and rest requirements because spatial allocations of equipment and facilities for work and recreation are generally determined together. Subsection 4.7.4 includes simple physical conditioning devices such as bungee cords used in physical therapeutic applications. Generally, these same devices can also be used for recreational purposes. A more sophisticated physical conditioning device is the on-board centrifuge discussed in Subsection 4.8.3. This device may also be used for recreational activities. The characteristics of the living and recreational facilities included and their weight, volume, and power are given in Table 4-78. The scaling laws for living and recreational facilities are given in Table 4-79.

4.8.3 Gravity Conditioning

Gravity conditioning may be needed to alleviate any adverse effects of the zero-gravity environment on crew members and would be necessary to precondition the crewmen for re-entry and as a research tool, particularly in fractional-g force field experimentation. One method of providing gravity conditioning is to rotate the whole or selected modules of the spacecraft. A major consideration for a rotating laboratory is the increased demand for propellant as well as the requirement of unique devices such as counter balances, control moment gyros, and more complex stabilization and control systems. Major constraints are those imposed on interior arrangement and on crew functions and operations. The other method of providing gravity conditioning is through the use of an on-board centrifuge. This centrifuge would be centrally located in the spacecraft in the pressurized compartment. It could consist of dual counterrotating arm assemblies rotating about and structurally supported by a shaft with a centerline that coincides with the centerline of the spacecraft. Each arm assembly would have attached a personnel carrier to accommodate the subjects in vented space suits. The centrifuge would be driven by a motor, and controlled by a computer for programming operation and for storage of information for diagnosis or

Table 4-78

DESCRIPTION OF LIVING AND RECREATIONAL FACILITIES EQUIPMENT(*)

Equipment Description	Unit Description Weight, kg	 Volume, m^3	 Power, $watts_e$
Shower (includes hardware, but not water reserves)	27.20	1.65	100
Laundry, washing machine	68	0.76	300
Sleep Station, includes frame, restraint and plastic airlock covering reserve pressure suit	8.60	1.16	--
Oxygen masks	0.23	1.4×10^{-2}	--

(*)Partial listing only. Additional equipment constitutes part of crew support subsystem.

remedial purposes. Such a centrifuge was designed for MORL (References 4-120 and 4-121) and this unit is selected for inclusion in this subsystem. This centrifuge weighs 542 kg, has a swept volume of 41.4 m^3, and requires 600 watts of power only during its actual operation. Scaling laws for the

Table 4-79

DESIGN SCALING LAWS FOR LIVING AND RECREATIONAL FACILITIES

Weight = $(190 + 4.1ND)K + 8.83N$ kg

Volume = $(4.84 + 0.002383ND)K + 1.17415N$ m^3

Power = $4500NDK$ $watt_e$-hour

D = Mission duration in years

N = Number of crew members

K = A dummy variable = 0 when $D < 1/12$
= 1 when $D \geq 1/12$

centrifuge are shown in Table 4-80. The centrifuge is assumed to not be necessary for missions of less than 1 year, and thus the variable (K) indicates this assumption.

4.8.4 Instrumentation, Controls, and Lighting Provisions

The instrumentation, controls, and lighting provisions are concerned with those measurements, displays, controls, and timers needed by the crew accommodations subsystem for the operation of sleeping stations, showers, laundry, recreation, and gravity conditioning equipment. Also included is the lighting system required for the spacecraft operations. Table 4-81 gives details of the instrumentation, controls and lighting equipment included and their weight, volume, and power requirements. The related scaling laws based on the equipment in Table 4-81 are given in Table 4-82.

4.9 CONTROLS SUBSYSTEM

The controls subsystem includes all automatic and manual devices, functional controls, displays, and the process monitoring equipment required for the Life Support System and which are located at the mission module central control console. Temperature, pressure, flow rates and other types of

Table 4-80

DESIGN SCALING LAWS FOR GRAVITY CONDITIONING EQUIPMENT

Weight = 544K kg

Volume = 41K m^3 (Volume is swept volume of centrifuge)

Power = 600 f K watts_e

D = Mission duration in years

K = A dummy variable = 0 when $D < 1$
= 1 when $D \geq 1$

f = Centrifuge use factor = $\frac{\text{use time, hours/day}}{24}$

Table 4-81

DESCRIPTION OF CREW ACCOMMODATION SUBSYSTEM INSTRUMENTATION, CONTROLS, AND LIGHTING EQUIPMENT

Equipment Description	Unit Description*		
	Weight, kg	Volume, m^3	Power, $watts_e$
Measurement transducers	36	0.85×10^{-2}	80
Signal conditioners	9.05	0.565×10^{-2}	50
Display and control system	109	14.1×10^{-2}	263
Caution and warning system	6.8	0.565×10^{-2}	18
Timing equipment	15.8	1.41×10^{-2}	38
Event timers	20.7	2.54×10^{-2}	96
Lighting systems	22.6	1.69×10^{-2}	800

---

*For a nominal crew of 6 to 8 men.

sensors would be located at the control console along with the functional control equipment. The interconnecting wiring for these sensors and the devices at the central control console have also been included. It is assumed that duplicate controls are located at the individual functional equipment and their weight, volume, and power requirements have been incorporated in the parametric data for each particular equipment. Apollo and MORL data from References 4-122 and 4-123 have been reviewed and weight and volume data for sensors, wiring, and control console equipment have been obtained and correlated. On the basis of these correlations and the degree of complexities involved for the various functional methods the following scaling laws for this subsystem have been developed:

$$W_o = 15.1 + 0.07 \pi DL, \text{ kg} \qquad (4\text{-}192a)$$

$$W_{pc} = 7.64 + 0.81 \pi DL, \text{ kg} \qquad (4\text{-}192b)$$

Table 4-82

DESIGN SCALING LAWS FOR CREW ACCOMMODATION SUBSYSTEM INSTRUMENTATION, CONTROLS, AND LIGHTING EQUIPMENT

Weight = 221 (0.08N + 0.2) kg

Volume = 0.22 (0.08N + 0.2) m^3

Power = 1345 (0.08N + 0.2) watts_e

N = Number of crew members

$$W_c = 12.7 + 1.03 \pi DL, \text{ kg} \quad (4\text{-}192c)$$

$$V_o = 0.03, \text{ m}^3 \quad (4\text{-}193a)$$

$$V_{pc} = 0.06, \text{ m}^3 \quad (4\text{-}193b)$$

$$V_c = 0.09, \text{ m}^3 \quad (4\text{-}193c)$$

where

W = Controls subsystem weight, kg
V = Control subsystem volume, m^3
D = Vehicle diameter, m
L = Total length of occupied cabins, m

subscripts

o = Open system
pc = Partially closed system
c = Closed system

Power requirement for the control subsystem is negligible.

4.10 SPARES PROVISIONING

Detailed reliability analyses have been prepared for the Atmosphere Control, Thermal Control, Waste Management, and Water Supply Subsystems. Existing mean time between failure (MTBF) data have been collected for the various equipment in each of these subsystems and these data have been reported in Reference 4-124. These reliability analyses have determined spare part requirements as a function of subsystem reliability for ranges of crew sizes and mission duration. The spare parts have been determined for particular functional methods in each of the subsystems. Table 4-83 shows the functional methods which were used. The results have been determined upon the basis of the weight of spares per unit weight of subsystem and are thus considered to be nearly as applicable to other functional methods as to those used in the analyses. This assumes that the general level of ecological closure is similar. The level of ecological closure involved in these detailed analyses has been that of the partially closed system where the oxygen and water are recovered and all food is stored. Degree of ecological closure of the system affects the Atmosphere Control and Water Supply Subsystems spare part requirements most significantly as oxygen recovery and water recovery equipment are a part of these subsystems and this recovery equipment is less well developed and less reliable than the other equipment in the systems. The spare part lists for systems are dominated by recovery equipment when system closure requires recovery. The open system does not include this recovery equipment and consequently it requires relatively few parts to attain a reasonably high degree of reliability. The closed system is, of course, more complicated than the partially closed system for it involves the addition of food processing equipment. As may be implied, reliability analyses have not been obtained for this system for none of the equipment has been built. The Atmosphere Control Subsystem potentially becomes less critical in terms of required spares in that the equipment required to process CO_2 for O_2 recovery is greatly reduced, or possibly not being required at all. The food processing equipment requires all, or at least a great part of the collected CO_2.

The detailed reliability analyses have been obtained through the use of an existing MDAC-WD computer program, The 0A16 Spares Provisioning Program. This program requires that the subsystem component weights and

Table 4-83

SELECTED FUNCTIONAL METHODS FOR RELIABILITY ANALYSES

Subsystem	Function	Functional Method
Atmosphere Control	Atmospheric gas storage	High pressure
	CO_2 reduction	Sabatier - Acetylene
	O_2 generation	Ion exchange membrane (electrolysis)
Water Supply	Water Recovery	Electrodialysis
		Multifiltration
		Pasteurization
Waste Management	Fecal collection	Vacuum dehydration
	Urine collection	Collected for water recovery
	CO_2 removal	Molecular sieve/silica gen
Thermal Control	Temperature and humidity control	Cabin heat exchanger and condenser
	Heat rejection	Cooling and radiator loops

MTBF data and mission duration must be specified for each case. Spares weights have been determined versus the particular equipment reliability. The basic procedure is that a series arrangement of all components is assumed, and the Poisson probability function is used for predicting the failure of each component and the number of its replacement spares. Spares are accrued in the most efficient manner for the entire system. The computer program prepares a list of incremental reliabilities divided by spare part weights and the list is arranged in descending order of numerical value. Increasing reliability is obtained by successively summing these incremental reliabilities and adding corresponding spare parts in the given determined order (Reference 4-125).

The assumed vehicle model used in these analyses is considered to have a single cabin. However, the results are considered to be equally applicable to multi-cabin vehicles for Thermal Control and Water Supply are considered, to be largely independent of compartmentation and using the determined spares data for these subsystems is directly applicable. Atmosphere Control and Waste Management are significantly affected by compartmentation in that for this study, the least reliable of the associated equipment were considered to be located in each individual cabin. These duplicated items include O_2 recovery equipment and CO_2 and trace contaminants removal equipment. This condition has been accounted for in the computations by using specified Equipment Design crew fractions per cabin and thus establishing subsystem redundancy. For example, when Equipment Design crew fractions per cabin are specified at 1.0 for a two-cabin vehicle, it is assumed that the Atmosphere Control and Waste Management Subsystems are 100% redundant, one complete subsystem in each cabin. Computed spares weight to subsystem weight ratios may then be decreased by 1.0 in determining required spares to satisfy a given subsystem reliability.

Tables 4-84, 4-85, 4-86, and 4-87 detail the subsystem equipment items, weights and the MTBF data used in obtaining the reliability analyses. Figure 4-75 shows typical computed spares weight ratio data for the Atmosphere Control Subsystem for a 20-man crew. Tables 4-88, 4-89, 4-90, and 4-91 show the computed reliability analyses results for the four subsystems considered. As indicated on Figure 4-75, which is a plot of Table 4-88, plots of these tabulated results on reliability paper may be taken as straight line segments between successive pairs of data.

Table 4-84
ATMOSPHERE CONTROL SUBSYSTEM

			Component Weight, kg		
No. of Components	Component	MTBF (hr)	2-Man System	10-Man System	20-Man System
1	Manifold	200,000,000	3.21	5.84	7.83
13	Valve	167,000	0.23	0.23	0.23
1	Blower	125,000	1.13	2.04	2.76
2	Regenerative-heat exchanger	167,000	7.25	12.65	17.00
1	CO_2 reactor	50,000	10.50	16.00	21.60
1	Condenser/H_2O separator	60.000	7.25	12.65	17.00
1	Water pump	66,700	3.21	58.45	7.83
5	Control valve	100,000	0.90	0.90	0.90
1	Electrolysis unit	100,000	16.30	28.95	38.90
2	Manual valve	167,000	0.45	0.45	0.45
1	H_2 accumulator	2,000,000	4.99	8.59	11.60
1	CH_4 reactor	40,000	14.11	24.90	33.50
1	Pressure sensor	100,000	1.36	1.36	1.36
3	Pressure reducer	100,000	0.90	1.36	1.36
2	Pressure controller	100,000	0.90	0.90	0.90
2	N_2 heat exchanger	167,000	0.45	0.90	1.26
1	O_2 sensor	100,000	1.36	1.26	1.26
2	O_2 heat exchanger	167,000	0.45	0.90	1.26
2	O_2 tank	24,000,000	32.10	102.00	171.00
1	N_2 tank	24,000,000	38.90	79.50	119.00
	TOTAL		195.71	485.43	657.95

Table 4-85

WATER SUPPLY SUBSYSTEM

No. of Components	Component	MTBF (hr)	Component Weight, kg 2-Man System	10-Man System	20-Man System
5	Pump	66,700	0.63	1.18	1.63
46	Valve	167,000	0.23	0.23	0.23
1	Temp. storage tank	1.0×10^8	0.45	1.13	1.81
1	Temp. storage tank	1.0×10^8	0.90	4.50	8.15
1	Temp. storage tank	1.0×10^8	0.32	1.58	2.85
3	Stby storage tank	1.0×10^8	2.89	14.50	26.00
2	UV light	40,000	1.81	1.81	1.81
1	Potable water tank	1.0×10^8	15.90	26.50	47.50
1	Charcoal bed	667,000	0.45	0.45	0.45
1	Charcoal filter	667,000	0.82	0.82	0.82
1	Agent tank	1,000,000	2.56	6.88	12.40
1	Mixing tank	1,000,000	0.32	1.58	2.85
1	Charcoal filter	667,000	1.31	1.31	1.31
1	Filter	667,000	0.45	0.45	0.45
1	Mixing tank	1,000,000	2.89	14.50	26.00
1	Charcoal filter	667,000	0.45	0.45	0.45
1	Conductivity probe	100,000	0.45	0.45	0.45
1	High flow electrodialysis unit	667,000	1.36	1.76	2.40
1	Membrane	667,000	0.32	0.59	0.77
1	Electrodialysis stack	667,000	0.95	1.76	2.40
2	Gas-liquid separator	1,000,000	0.45	0.45	0.45
2	Three-way valve	100,000	0.90	0.90	0.90
	TOTAL		58.62	131.01	214.11

Table 4-86

WASTE MANAGEMENT SUBSYSTEM

			Component Weight, kg		
No. of Components	Component	MTBF (hr)	2-Man System	10-Man System	20-Man System
1	Debris trap	20,000	0.23	0.23	0.23
4	Fan/blower	125,000	2.90	5.[illegible]4	7.06
2	Condenser/H_2O Separator	60,000	4.35	7.89	10.58
7	Diverter valve	100,000	1.36	1.36	1.36
2	Silica gel canister	200,000	0.18	0.72	1.36
1	Heat exchanger	167,000	3.40	6.11	8.29
2	CO_2 sorber	200,000	0.36	1.63	2.90
8	Valve	167,000	0.23	0.23	0.23
1	Odor remover	200,000	1.13	2.03	2.76
1	Filter	200,000	0.77	1.49	2.04
1	UV light	40,000	1.81	1.81	1.81
1	Chemi-sorber	100,000	2.58	4.66	6.30
1	Regenerative heat exchanger	167,000	1.45	2.62	3.53
1	Catalytic burner	100,000	1.58	2.94	3.93
1	Vacuum pump	57,100	8.89	16.0	39.60
1	Accumulator	1,000,000	5.19	9.31	12.60
2	Valve	100,000	0.90	0.90	0.90
2	Filter	200,000	0.63	1.17	1.63
1	Liquid-gas separator	200,000	2.66	4.75	6.48
3	Collectors	667,000	1.36	1.36	1.36
1	Seat and frame	2,000,000	6.29	6.29	6.29
	TOTAL		75.86	119.26	172.28

Table 4-87
THERMAL CONTROL SUBSYSTEM

No. of Components	Component	MTBF (hr)	Component Weight, kg 2-Man System	 10-Man System	 20-Man System
2	Pump	66,700	0.56	0.56	0.56
10	Check valve	167,000	0.23	0.23	0.23
10	Stop valve	167,000	0.23	0.23	0.23
1	Temperature control valve	100,000	0.90	0.90	0.90
1	Reservoir	667,000	9.00	9.00	9.00
	TOTAL		15.62	15.62	15.62

Table 4-88
SPARES FOR ATMOSPHERE CONTROL SUBSYSTEM

System Size	Mission Duration, days 90	 180	 400	 800	 2,000
2-Man System	0.25 (0.9)	0.4 (0.9)	0.64 (0.9)		
	0.96 (0.99945)	1.18 (0.99928)	1.22 (0.9993)		
	1.56 (0.9999)	1.9 (0.9999)	2.4 (0.9999)		
10-Man System	0.16 (0.9)	0.24 (0.9)	0.4 (0.9)		
	0.7 (0.99965)	0.8 (0.99932)	0.82 (0.9972)		
	1.26 (0.9999)	1.7 (0.9999)	2.08 (0.9999)		
20-Man System	0.08 (0.9)	0.2 (0.9)	0.4 (0.9)		1.02 (0.9)
	0.66 (0.99962)	0.76 (0.99933)	0.67 (0.993)		1.25 (0.975)
	1.45 (0.9999)	1.68 (0.9999)	1.9 (0.9999)		2.88 (0.9999)

Note: Pairs of points denote ratio of spares weight to subsystem weight and corresponding subsystem reliability.

Table 4-89

SPARES FOR WATER SUPPLY SUBSYSTEM

System Size	Mission Duration, days 90	180	400	800	2,000
2-Man System	0.54 (0.9) 2.04 (0.9999)		0.84 (0.9) 2.56 (0.9999)		1.96 (0.9) 4.32 (0.9999)
10-Man System	0.15 (0.9) 1.3 (0.9999)		0.55 (0.9) 1.9 (0.9999)	0.85 (0.9) 2.45 (0.9999)	1.38 (0.9) 3.26 (0.9999)
20-Man System					

Note: Pairs of points denote ratio of spares weight to subsystem weight and corresponding subsystem reliability.

Table 4-90

SPARES FOR WASTE MANAGEMENT SUBSYSTEM

System Size	Mission Duration, days 90	180	400	800	2,000
2-Man System					
10-Man System	0.56 (0.9) 2.0 (0.9999)	0.82 (0.9) 2.42 (0.9999)		1.7 (0.9) 3.92 (0.9999)	2.8 (0.9) 5.55 (0.9999)
20-Man System					

Note: Pairs of points denote ratio of spares weight to subsystem weight and corresponding subsystem reliability.

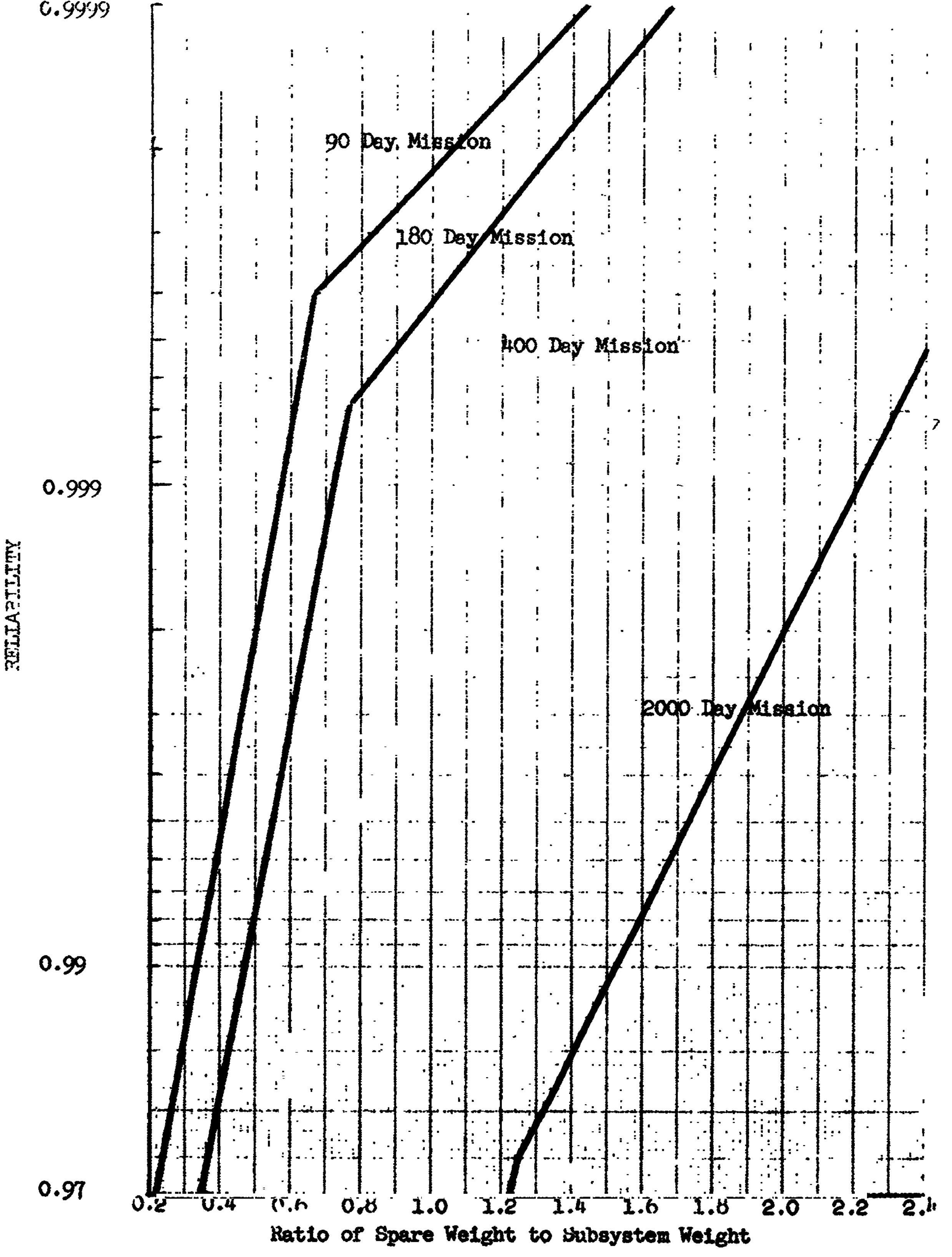


Figure 4-75. Spares for Atmosphere Control Subsystem (20-Man Life Support System)

Table 4-91

SPARES FOR THERMAL CONTROL SUBSYSTEM

System Size	Mission Duration, days				
	90	180	400	800	2,000
All systems (independent of crew size)	0.5 (0.9)		1.13 (0.9)		2.28 (0.9)
	1.8 (0.9999)		2.74 (0.9999)		4.72 (0.9999)

Note: Pairs of points denote ratio of spares weight to subsystem weight and corresponding subsystem reliability.

4.11. REFERENCES

4-1. Zimmerman, R. H. Equipment Cooling Systems for Aircraft. AirForce Report Number WADC-TR-54-359, 1954.

4-2. Zimmerman, R. H., et al. Artificial Cabin Atmosphere. Air Force Report Number WADC-TR-55-353, 1955.

4-3. Blakely, R. L., and Barker, R. S. The G-189 Generalized Environmental Control and Life Support System Fortran Program, Volume IV. May 1966.

4-4. Yakut, M. M., and Barker, R. S. Thermal and Atmospheric Control Components Weights. MDAC-WD Report. SM-47867, May 1965.

ATMOSPHERE CONTROL SUBSYSTEM

4-5. Roth, E. M. Space-Cabin Atmospheres, Part III, Physiological Factors of Inert Gases. NASA SP-117, 1967.

4-6. Kirkland, V. D., et al. Study to Evaluate the Usefulness of the MOL to Accomplish Early NASA Mission Objectives. MDAC-WD Report DAC-58014, May 1967 (Confidential).

4-7. Bonura, M. S., et al. Engineering Criteria for Spacecraft Cabin Atmosphere Selection. NASA CR-891, September 1967.

4-8. Coe, C. S., et al. Analytical Methods for Space Vehicle Atmospheric Control Processes. ASD-TR-61-162, Part II, November 1962.

4-9. Atmospheric Control Systems for Space Vehicles. ASD-TDR-62-527, March 1963.

4-10. Clark, L. G. Carbon Dioxide Reduction Unit Operation with Bosch Reaction. Langely Research Center Paper, LWP-387, March 1967.

4-11. Babinsky, A. D. CO_2 Reduction Unit Designed for Continuous Zero Gravity Operation. TRW Report 54060, April 1964.

4-12. Foster, J. F., and McNutly, J. S. Study of a Carbon Dioxide Reduction System. ASD TR-61-388, August 1961.

4-13. Remus, G. A., et al. Carbon Dioxide Reduction System. AMRL-TDR-63-7, January 1963.

4-14. Clifford, J. E. Battelle Memorial Institute, Personal Communication, February 1968.

4-15. Macklin, M. R. Advanced Oxygen Regeneration System. TRW, Inc., Report Number ER-6289, 3 November 1964.

4-16. Babinsky, A. D., and Walsh, T. J. Continuous Atmosphere Control Using a Closed Oxygen Cycle. Presented to the American Institute of Chemical Engineers, February 1965.

4-17. Armstrong, R. C. Life Support System for Space Flights of Extended Durations. NASA Report Number CR-614, November 1966.

4-18. Armstrong, R. C. Redesign of the CO_2 Reduction Unit. General Dynamics Convair Report 64-26229, 12 August 1965.

4-19. Drake, G. L., and Burnett, J. R. Selection of an Oxygen Regenerating System to Meet the Demands of a Multi-Mission Program. Presented to the American Society of Automotive Engineers, 26 October 1967.

4-20. Stein, P. J. Research and Development Program for a Combined Carbon Dioxide Removal and Reduction System. Hamilton Standard Division, Contract No. NAS1-4154, Final Report - Phase I, October 1965.

4-21. Chandler, H. W., and Oser, W. Study of Electrolytic Reduction of Carbon Dioxide. Technical Documentary Report Number MRL-TDR-62-16, 1962.

4-22. Taylor, T. I. Electrolytic Reduction of O_2 from CO_2. U. S. Patent Office Number 3 079 237, 26 February 1963.

4-23. Chandler, H. W. Carbon Dioxide Reduction System. Isomet Corporation, Contract No. AF33(657)-8066, Report No. AMRL-TDR-64-42, May 1964.

4-24. Chandler, H. W. Design of a Test Model for a Solid Electrolyte Carbon Dioxide Reduction System.

4-25. Chandler, H. W., and Howell, L. J. A Solid Electrolyte Carbon Dioxide Reduction System. Aerospace Medical Research Laboratories Report AMRL-TR-67-209, January 1968.

4-26. Weissbart, J., and Smart, W. H. Study of Electrolytic Dissociation of CO_2 - H_2O using a Solid Oxide Electrolyte. NASA Report Number CR-680, February 1967.

4-27. Jackson, J. K., et al. Sixty Day Test of an Advanced Integrated Life Support System in a Space Cabin Simulator. MDAC-WD Astronautics Company Report DAC-62295, October 1968.

4-28. Thompson, E. B. Investigation of Catalytic Reactions for CO_2 Reduction. FDL-TDR-64-22 Part V, May 1967.

4-29. Withee, W. W. Study for Basic Subsystem Module Preliminary Definition. General Dynamics Convair. Report Number GDC-DAB67-003.

4-30. Adlhart, O. J., and Hartner, A. J. Experimental Evaluation of Precious Metal Carbon Dioxide Catalysts. Air Force Flight Dynamics Laboratory Report Number AFFDL-TR-67-80, May 1967.

4-31. Glueckert, A. J., and Remus, G. A. Advanced Concept of a Laboratory-Type Oxygen Reclamation System for Manned Spacecraft. General American Transportation Corporation. Report Number GARD-1288-6080, 5 May 1967.

4-32. Hower, K. L., et al. Design of an Atmosphere Regeneration System. Air Force Flight Dynamics Laboratory Report Number AFFDL-TR-65-232, August 1966.

4-33. Marshall, D. W. Catalytic Oxidation of Methane At Low Space Velocities. Air Force Flight Dynamics Laboratory Report Number AFFDL-TR-66-56, June 1966.

4-34. Remus, G. A., et al. Catalytic Reduction of Carbon Dioxide to Methane and Water. Report Number AFFDL-TR-65-12, April 1965.

4-35. Ames, R. K. Methane Hydrogen Plasma for Sabatier System Extension. Presented to American Society of Mechanical Engineers, 16-19 June 1968.

4-36. Ames, R. K. Present Status of the Sabatier Life Support System. American Society of Mechanical Engineers Paper Number 63-AHGT-48, March 1963.

4-37. Clifford, J. E., et al. Investigation of an Integrated Carbon Dioxide-Reduction and Water-Electrolysis System. Report Number AMRL-TDR-66-186, April 1967.

4-38. Clifford, J. E., and Faust, C. L. Research on the Electrolysis of Water with Hydrogen Diffusion Cathode to be used in a Rotating Cell. Air Force Report Number AMRL-TDR-62-94, August 1962.

4-39. Clifford, J. E., et al. Research on a Gravity-Independent Water-Electrolysis Cell with a Palladium-Silver Cathode. Air Force Report Number AMRL-TDR-64-44, June 1964.

4-40. Clifford, J. E., et al. Development of a Rotating Water Electrolysis Unit. Air Force Flight Dynamics Laboratory AFFDL-TR-67-111, July 1967.

4-41. G. L. Fogal. General Electric Missile and Space Vehicle Division, Private Communication, July 1967.

4-42. Clifford, J. E., et al. A Water-Vapor Electrolysis Cell with Phosphoric Acid Electrolyte. Battelle Memorial Institute Report, Contract Number NAS2-2156, September 1966.

4-43. Clifford, J. E., et al. Research on the Electrolysis of Water Under Weightless Conditions. Report Number MRL-TDR-62-44, May 1962.

4-44. Wydeven, T., and Smith, E. Water Vapor Electrolysis. Presented to the Aerospace Medical Association, April 1966.

4-45. Antony, A. P. Design and Fabrication of a Water Electrolysis Unit for an Integrated Life Support System. Report Number NASA CR-66654, August 1968.

4-46. Petheroff, C. W., et al. Electrolysis Cell for Orbital Test. Report Number NASA CR-648, 15 June 1966.

4-47. Armstrong, R. C. Oxygen Recovery System Evaluation for Space Flights of One Year Duration, General Dynamics Convair Report No. 64-26203, August 1963.

4-48. Antony, A. P., Allis-Chalmers Corporation, Advanced Electrochemical Products Division, Milwaukee, Wisconsin, Private Communication, February-April 1968.

THERMAL CONTROL SUBSYSTEM

4-49. Byke, R. M., and Brose, H. F. Report on the Optimization of the Manned Orbital Research Laboratory (MORL) System Concept. MDAC-WD Report SM-46085, Volume XIX, Laboratory Mechanical Systems - Environmental Control/Life Support, September 1964.

4-50. Marion, E. D. High Performance Insulation System Development Interim Report. MDAC-WD Report DAC-57963, January 1967.

4-51. Wilson, D. G., et al. The Design and Performance Analysis of Compact Heat Exchanges. Published by the Northern Research and Engineering Corporation, Cambridge, Massachusetts, 1965.

4-52. Kreith, F. Principles of Heat Transfer, 2nd Edition, International Textbook Company, Scranton, Pennsylvania, 1965.

4-53. Bonura, M. S., Nelson, W. G., et al. Engineering Criteria for Spacecraft Cabin Atmosphere Selection, NASA CR-891, September 1967.

4-54. Ledford, O. C., and Stiehm, M. J. Manned Spacecraft Radiator Analysis, Douglas Report DAC-56485, unpublished.

4-55. Barker, R. S., et al. Design and Transient Performance of a Liquid Coolant System, Paper 6703838, Society of Automotive Engineers, Presented at Aeronautic and Space Engineering and Manufacturing Meeting, Los Angeles, California, October 1967.

4-56. Watt, R. G. Radiant Heat Transfer to Earth Satellites. Paper 64-WA/HT-28 American Society of Mechanical Engineers, Presented at Winter Annual Meeting, New York, New York, December 1964.

4-57. Withee, W. W. Study for Basic Subsystem Module Preliminary Definition, Final Report, Volume VI, Environmental Control and Life Support. General Dynamics, Convair Division, October 1967.

4-58. Anderson, A. F., et al. Radiator Design for Space Vehicles. AiResearch Manufacturing Company Report MS-AP0069, 1963.

4-59. Bartas, J. G., and Sellers, W. H. "Radiation Fin Effectiveness." Trans. Asme, Series C, Journal of Heat Transfer, 82, 73-75 (1960).

4-60. Thermal Conditioning Structures and Fluxless Brazing. Brochure published by AVCO Corporation, Aerospace Structures Division, Nashville, Tennessee.

4-61. Bacha, C. P., et al. Temperature Control Systems for Space Vehicles. ASD-TDR-62-493, Part II, May 1963.

4-62. Kays, W. M., and London, A. L. Compact Heat Exchangers. McGraw Hill Book Company, New York, New York, 1964.

WATER SUPPLY SUBSYSTEM

4-63. Putnam, D. F. Water Management for Extended-Duration Manned Space Missions. MDAC-WD Paper Number DP-4576, Presented to Conference on Bioastronautics, Virginia Polytechnic Institute, Blacksburg, Virginia, August 1967.

4-64. Putnam, D. F. Chemical Aspects of Urine Distillation. ASME 65-AV-24, American Society of Mechanical Engineers, New York, 1965.

4-65. Water Reclamation Subsystem Supplement. Ionics, Inc., Report Number II-P-63-23A, August 1963.

4-66. Esten, R. W., et al. An Advanced Technique for Water Recovery. Presented to the American Institute of Chemical Engineers, New York, 1967.

4-67. Wallman, H., et al. Multi-Filter System for Water Reclamation. Aerospace Medicine, January 1965.

4-68. Hansen, C. The Marquardt Corporation, Personal Communications, July 1967.

4-69. Withee, W. W. Study for Basic Subsystem Module Preliminary Definition. General Dynamics, Convair Division Report Number GDC-DAB67003, October 1967.

4-70. Manned Planetary Flyby Missions Based on Saturn/Apollo Systems, Part I Environmental Control and Life Support. North American Aviation, Inc., Report No. SID 67-549-6-1, August 1967.

4-71. Barker, R. S., et al. Design and Transient Performance of a Liquid Coolant System. MDAC-WD Paper 4505, October 1967.

4-72. Report on the Optimization of the Manned Orbital Research Laboratory (MORL) System Concept, Volume XIV Laboratory Mechanical Systems - Environmental Control/Life Support. MDAC-WD Report SM-46085, September 1964.

WASTE MANAGEMENT SUBSYSTEM

4-73. Coe, C. S., et al. Analytical Methods for Space Vehicle Atmospheric Control Processes Part II. ASD TR 61 162, November 1962.

4-74. Byrne, J. P. Environmental Control and Life Support System for Apollo Application Program. AiResearch Manufacturing Company Report Number SS 3419-3, Rev. 1, 25 August 1967.

4-75. Sherwood, T. K., and Pigford, R. L. McGraw Hill Book Cc ay, New York, New York, 1952.

4-76. Brown, D. L. Investigation of an Electrochemical Device for Carbon Dioxide Absorption and Oxygen Generation. ASD TDR 63 441, May 1963.

4-77. McConnaughey, W. E., et al. Removal of CO_2 from Submarine Atmospheres by Amine Resins. NRL 5022, November 1957.

4-78. Rohm and Haas Co., Resinous Products Division, Philadelphia, Pa.

4-79. Premuitt Company, New York, N. Y., Products Literature.

4-80. Glueckert, A. J., et al. GAT O SORB A Regenerable Sorbent for Carbon Dioxide Control. Presented to The Society of Automotive Engineers, 26 October 1967.

4-81. Babinsky, A. D., et al. Carbon Dioxide Concentration System. TRW Equipment Laboratories, Contract No. NAS 7638, Report No. 72086, July 1966.

4-82. Macklin, M. Active Electrolytic Concentration of Carbon Dioxide. Electrochemical Technology, Vol. 4, No. 9-10, September-October 1966.

4-83. Jackson, J. K., and Blakely, R. L. Application of Adsorption Beds to Spacecraft Life Support Systems. Presented to the Society of Automotive Engineers, 2-6 October 1967.

4-84. Byke, R. M. Evaluation of the Usefulness of the MOL to Accomplish Early NASA Mission Objectives, MDAC-WD Report Number DAC-58014, May 1967.

4-85. Withee, W. W. Study for Basic Subsystem Module Preliminary Definition Final Report, Volume VI. Convair Report Number GDC-DAB67-003, October 1967.

4-86. Human Waste Collection and Storage During Aerospace Flight. Aerospace Medical Research Laboratories AMRL-TDR-64-3, February 1964.

4-87. Mars Landing and Reconnaissance Mission Environmental Control and Life Support System Study, Vol. 2 Subsystem Studies, Hamilton Standard Division of United Aircraft Corporation, 1964.

4-88. Report on the Development of the Manned Orbital Research Laboratory (MORL) System Utilization Potential. MDAC-WD Report Number SM-48816, December 1965.

4-89. Water and Waste Management Subsystem for NASA Basic Subsystem Module. Marquardt Corporation MR20,404, Interim Report, June 1967.

4-90. Waste Management Subsystem for MOL. Douglas Technical Requirement Specification No. TR00507, 12 August 1966.

4-91. Bioastronautics Data Book. NASA SP-3006, 1964.

4-92. Apollo Applications Program - Waste Management System. GARD Report 1276-9598, GATC-GARD, 31 March 1967.

4-93. MOL Waste Management System, Vol. I Technical. TRW Systems, 24 October 1966.

4-94. Extended Mission Apollo Spacecraft Phase I-A Studies on Water Reclamation, Waste Management, Personal Hygiene. GATC Report MRP 1276-5060, Fall 1965, GATC-MTD Div.

4-95. MOL/WM S/EDP Program. Technical Proposal, Vol. I. Marquardt Corporation, 24 October 1966.

4-96. Research and Development o Waste Management Unit for a Manned Space Vehicle. Aerospace Medical Research Laboratory, AMRL-TR-67-2, April 1967.

FOOD SUPPLY SUBSYSTEM

4-97. Sinyan, Yu. Ye. The Possibility of Physiochemical Synthesis of Carbohydrates in a Spaceship Cabin. Problems of Space Biology, Vol. 3, 3 June 1964.

4-98. Deichman, W. Industrial Medicine, Vol. 9, 1940.

4-99. Johnson, V., et al. American Journal of Physiology, Vol. 103, 1933.

4-100. Gil'Miyarova, F. N. Transactions of KUIBYSHEVSK MED. INST., Vol. 29, 1964.

4-101. Study of Life Support Systems for Space Missions Exceeding One Year in Duration. Lockheed Report No. 4-06-6606, 15 March 1966.

4-102. Faith, W., et al. Industrial Chemicals. Wiley, New York, 1964.

4-103. Kirk, R., and Othmer, D. Encyclopedia of Chemical Technology, Vol. 9, Interscience, 1952.

4-104. Walker, J. Formaldehyde. Reinhold, New York, 1964.

4-105. Kirk, R., and Othermer, D. Encyclopedia of Chemical Technology. Vol. 4. 1952.

4-106. Seyewetz, A. Bulletin de la Societe de Chimie. Vol. 3, 1904.

CREW AND CREW SUPPORT SUBSYSTEM

4-107. Jones, S. Design Criteria and Guidelines for Use of the Apollo Space Suit Assembly (ASSA) for an S-IVB Workshop Mission. Memorandum R-P & VE-AL-65-150, George C. Marshall Space Flight Center, Huntsville, Alabama, 21 October 1965.

4-108. Final Report on RX-1, RX-2 and RX-2-A, Suit Development. Litton Systems, Inc., Beverly Hills, California, Publication No. 4259, 1965 (Confidential).

4-109. Richardson, D. L. Research to Advance Extravehicular Protective Technology. Air Force Report No. AMRL-TR-66-250, April 1967.

4-110. Normyle, W. J. Lunar Astronauts to Use New Oxygen Pack. Aviation Week and Space Technology, 3 June 1968.

4-111. Apollo Portable Life Support System Component Data Summary. Hamilton Standard Division of United Aircraft Corporation, Report No. SLS-611A, October 1966.

4-112. Kincaid, W. C. Apollo Portable Life Support System Development Status. Presented at ASME meeting, Los Angeles, March 1965.

4-113. Experiment Implementation Plan for Manned Space Flight Experiment, S-IVB Orbital Workshop Experiment No. M-508, Astronaut Maneuvering Unit Experiment. George C. Marshall Space Flight Center, 6 May 1968.

4-114. Experiment Implementation Plan for Manned Space Flight Experiment, S-IVB Orbital Workshop Experiment No. M-509, Astronaut Maneuvering Unit Experiment. George C. Marshall Space Flight Center, 12 December 1968.

4-115. Proceedings of the National Conference on Space Maintenance and Extra-Vehicular Activities, Orlando, Florida, 1-3 March 1966.

4-116. Generay Independent TC Mobile Diagnostic X-Ray Unit, Code 802508, F. Clair Morgan Co., Inc., Standard X-Ray Co., 1031 West 9th Street, Los Angeles 6, California.

4-117. Preliminary Technical Data for Earth Orbiting Space Station. MSC-EA-R-66-1, Volumes 1 and 2. National Aeronautics and Space Administration, Manned Spacecraft Center, 7 November 1966.

4-118. Experiment Implementation Plan for Manned Space Flight Experiment, S-IVB Orbital Workshop Experiment No. M-487. Habitability/Crew Quarters Experiment, Payload Integration Document, George C. Marshall Space Flight Center, 12 June 1967.

CREW ACCOMMODATIONS SUBSYSTEM

4-119. Investigation of Aerospace Vehicle Crew Station Criteria. Air Force Report No. FDL-TDR-64-86, 31 July 1964.

4-120. White, W. J. A Space-Based Centrifuge--1965 Status Report. MDAC-WD Paper No. DP-3436, October 1965.

4-121. Report on a System Comparison and Selection Study of a Manned Orbital Research Laboratory (MORL), Volume I, Technical Summary. MDAC-WD Report No. SM-44604, September 1963.

CONTROLS SUBSYSTEM

4-122. Environmental Control and Life Support System for Apollo Application Program. AiResearch Manufacturing Company Report No. SS-3414-3, Volume III, Parts 2A and 2B, 1967.

4-123. Byke, R. M., and Brose, H. F. Report on the Optimization of the Manned Orbital Research Laboratory (MORL) System Concept. Douglas Report SM-46085, Volume XIX, Laboratory Mechanical Systems - Environmental Control/Life Support, September 1964.

SPARES PROVISIONING

4-124. Manned Mars Exploration in the Unfavorable (1975-1985) Time Period. Douglas Report No. SM-45582, February 1964.

4-125. Study of Conjunction Class Manned Mars Trips, Part II. Douglas Report No. SM-48662, June 1965.

Section 5
CONCLUSIONS AND RECOMMENDATIONS

Parametric relations and scaling laws have been developed that can be used to describe life support systems with varying degrees of closure from fully open to fully closed. Life support systems using the parametric data can be defined and characterized considering the inputs from and interdependencies of mission analysis variables such as mission duration, flight path, target planet, meteoroid and radiation hazard, and crew size.

The latest available data were used to derive the parametric data and to establish mathematical models. Several alternate methods were selected that may be used to depict each of the functional life support system processes. For each, individual parametric data and analytical relationships data were formulated for the weight, volume, power, heating, and cooling requirements of the equipment elements of each of eight subsystems comprising spacecraft life support systems. These subsystems are those for atmosphere control, thermal control, water supply, waste management, food supply, crew and crew support, crew accommodations, and system controls.

Sensitivity analyses were performed during the development of the computational logic and the parametric data. A Fortran program was developed to mechanize the computational procedures. This program is described in Volume III. A detailed discussion and description of the program is given in Volume IV.

Recommendations for further effort include the following:

1. **Sensitivity analysis has indicated that major weight, volume, and power contributions were made by items normally neglected in many life support tradeoff studies. Such items include a human centrifuge, personal hygiene, and other personnel equipment. Refinement of scaling laws is recommended in these areas.**

2. Development of scaling laws for additional life support functional methods not included in the study is also recommended. For example, major weight savings may be obtained for many missions by recovering atmospheric supply cryogenic boiloff by a refrigeration-reliquefaction system, recovering usable gases from electrolytic pretreatment, and by using isotope heat sources integrated with life support systems where heat is needed for regeneration or for the process. Electric attitude control systems utilizing waste byproducts may provide weight savings for some missions. For example, if the thrusting requirement is low in high-earth orbit, a Sabatier unit with its waste methane vented to a resistojet type attitude control system might be comparable in total vehicle weight to using a Bosch oxygen recovery unit with the conventional attitude control system using hypergolic propellant. Other similar tradeoffs but considering utilization of different waste byproducts and arc jet or resistojet type attitude control systems are also recommended.
3. Continuous and future refinement of the developed scaling laws is recommended to incorporate analytical and technological advances in life support as they occur. This should include the addition of new concepts in functional methods as they are announced.
4. The interdependence between the life support and electrical power system is extremely important from a total penalty standpoint. Power penalty for the life support system can vary, for example, from several hundred pounds for each kilowatt up to the 1,800 lb/kW range depending upon the power to be supplied and the supplying system. More realistic mission analysis penalty evaluations would be possible if the life support and secondary power Fortran programs were integrated.