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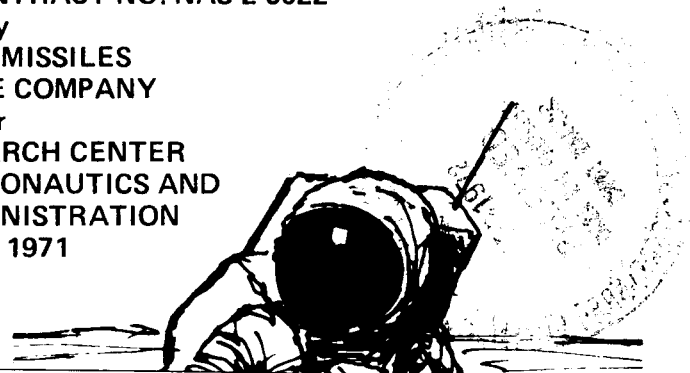
ADVANCED EXTRAVEHICULAR PROTECTIVE SYSTEMS (AEPS) STUDY

(INTERIM REPORT)

by
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and B. W. WEBBON

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for
AMES RESEARCH CENTER
NATIONAL AERONAUTICS AND
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AND SPACE COMPANY**

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FOREWORD

This report summarizes a study of Advanced Extravehicular Protective Systems (AEPS) for use in future missions in orbit, on the lunar surface, and on the Martian surface. The study concentrated on the origination of regenerable life support concepts, and included evaluation and selection of life support subsystems. This study was performed by the Vought Missiles and Space Company (VMSC) of LTV Aerospace Corporation during the period of July 1970 through May 1971 for the Environmental Control Branch of the Bio-Technology Division of NASA-Ames Research Center (ARC) under contract NAS 2-6022 supported by NASA Headquarters-OMSF, Bio-environmental System Division, RTOP No. 970-22-30.

The study originated subsystem concepts for performing life support functions in AEPS which are regenerable or partially regenerable. Expendable subsystems were also considered in the study. Parametric data for each subsystem concept were evolved including subsystem weight and volume, power requirement, thermal control requirement; base regeneration equipment weight and volume, power requirement, and the thermal control requirement; and expendable requirement. The most favorable subsystem concepts for each life support functional requirement were selected for more detailed study. These candidate concepts were subjected to a preliminary design analysis which refined the parametric data. In addition, system integration factors were considered for the candidate subsystems. Optimum subsystem concepts were selected for each mission, as were optimum total AEPS concepts.

Dr. Al Chambers of NASA-ARC was the Technical Monitor of this study. Mr. J. L. Williams of VMSC, the project engineer, managed the study, and was supported by Dr. R. J. Copeland who concentrated on oxygen supply and carbon dioxide control, and Mr. B. W. Webbon who concentrated on thermal control, trace contaminant control, and power supply.

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ABSTRACT

This report describes a study of life support subsystem concepts for Advanced Extravehicular Protective Systems (AEPS) intended for use on future orbital, lunar surface, and Mars surface missions in the late 1970's and 1980's. The specific subsystems considered were:

- Atmosphere Supply
- Carbon Dioxide Control
- Trace Contaminant Control
- Thermal Control
- Humidity Control
- Power Supply

Primary interest was centered around the thermal control and carbon dioxide control subsystems because they offer the greatest potential for total weight savings. Emphasis was placed on the generation of regenerable subsystem concepts; however, partially regenerable and expendable concepts were also considered. Previously conceived and developed subsystem concepts were included in the study. Concepts were evaluated on the basis of subsystem weight and volume, and subsystem contribution to parent vehicle weight and volume, which included spares, regeneration equipment, expendables, expendables storage penalty, power penalty, and process heating or cooling penalty. A preliminary analysis of all concepts was performed to reduce the field to the most outstanding concepts, which were then evaluated in detail. Results are presented showing total weight and volume penalty as a function of total mission Extravehicular Activity (EVA) hours, and showing EVA weight and volume as a function of EVA duration. Subsystem concepts are recommended for each life support function, and secondary concepts which should be developed are also identified.

1.0 INTRODUCTION

Space missions undertaken in the late 1970's and 1980's time frame may involve more ambitious Extravehicular Activity (EVA) than has been attempted on space missions through the Apollo Program. EVA's may be increased in sortie duration, sortie frequency, numbers of personnel involved, and scope. Current EVA life support equipment performs its functions through the use of expendable fluids and materials. The Apollo Portable Life Support System (PLSS) is an example of this type of equipment. On these future missions, the use of expendables will be prohibitive, and life support equipment which is regenerable in some measure will be required to make the missions viable.

The purpose of this study is to investigate possible means of accomplishing advanced EVA. Advanced Extravehicular Protective Systems (AEPS) for use in earth orbit, on the lunar surface, and on the Mars surface are considered. The complete range of possible subsystems for performing life support functions are considered, including expendable, partially regenerable, and regenerable techniques. Concepts which have previously been considered or used are included, and new concepts are evolved. The primary emphasis is placed in the areas which require the largest quantity of expendable material in current systems; that is, the thermal control subsystem, and the carbon dioxide control subsystem. Considerable attention is also given to the atmosphere supply subsystem, which may be integrated with the carbon dioxide control subsystem in some instances.

Guidelines and constraints are established to insure that the resulting AEPS subsystem selections are reasonable. Included in these guidelines and constraints are such factors as maximum AEPS backpack weight and volume, maximum support equipment transporter payload weight and volume, base power and thermal process penalties, and anticipated thermal environments. The thermal environments are established to aid in making an accurate and equitable comparison of the rate limited and the total capacity limited heat rejection systems. Data are generated for the specific missions considered in this evaluation. Data are also generated as a function of number of EVA sorties without identifying specific missions.

Optimum subsystem concepts are identified for the specific missions considered, and for various points as the number of sorties on a mission is increased. Optimum total AEPS concepts are identified and recommendations are made on the subsystem concepts which should be pursued.

2.0 STUDY OBJECTIVES AND APPROACH

2.1 Study Objectives

The future of manned exploration of space and the planetary bodies will be strongly influenced by the availability of effective and efficient portable life support equipment for use in extravehicular activity (EVA). The development of regenerable or partially regenerable systems for performing life support functions is central to the development of efficient Advanced Extravehicular Protective Systems (AEPS).

The specific objectives of this study are to:

- (1) Identify new concepts for providing life support functions in AEPS.
- (2) Make a realistic appraisal of regenerable and partially regenerable life support system concepts which are feasible for use in AEPS.
- (3) Identify the most promising life support functional concepts and techniques for AEPS, and make recommendations on the priority which should be assigned in the development of these components and techniques.

Secondary objectives of the study are to:

- (1) Identify trade factors relating to EVA support which should be considered in advanced spacecraft design and development.
- (2) Provide information for use in planning advanced space missions, including such factors as, (a) the influence of sortie duration on the size of life support equipment and expendables, (b) the number of sorties which will be available within specific primary vehicle weight and volume constraints, (c) the weight and volume requirements in the primary vehicle to support specific EVA objectives, and (d) the size, weight, and volume of future EVA equipment to allow assessment of limitations on maneuverability, flexibility, etc.

2.2 Study Approach

The approach taken to accomplish the study objectives was to:

- (1) Establish a set of ground rules and constraints which provide a framework which is flexible enough to consider the widest range of potential concepts, but which is specific enough to insure that all selected concepts are practical. There are currently no specific plans for space missions of extended duration beyond the 56 days of Skylab. Therefore, it was necessary to establish guidelines in a somewhat arbitrary fashion; using prior studies of advanced space missions as a baseline.

(2) Review the literature to identify techniques for accomplishing life support functions which have been used previously, not only in the space program, but also in commercial and industrial applications.

(3) Review the physical properties and equations governing the fundamental reactions involved in heat rejection and carbon dioxide control in order to identify concepts not previously considered.

(4) Perform a preliminary screening process to eliminate those concepts which appear less suitable.

(5) Perform detailed consumables analysis on the candidate concepts. Also perform a preliminary design of the candidate concepts to establish component size and weight, support equipment requirements, and to identify potential operational difficulties.

(6) Select the most promising concepts for each life support function for each specific type of mission considered, and for use on all missions.

3.0 GUIDELINES AND CONSTRAINTS

Studies to establish the configuration of future equipment are profoundly affected by the selection of guidelines and constraints. Very frequently this selection will be the dominant factor in the success with which the study results stand the test of time. The United States currently has no long-range congressional commitment to any space program beyond the current Apollo and Skylab (formerly Apollo Applications Program [AAP]) programs. However, it is necessary to postulate the missions and mission sequencing which will be undertaken by the United States, so that guidelines and constraints which affect significant trade factors such as power penalty, crew size, mission duration, etc. can be assessed in a reasonable manner.

Several studies have been conducted which indicate the types of missions which might be undertaken in the next two decades. The most significant of these are the NASA report on "America's Next Decades in Space" (Reference [1]) prepared for the Space Task Group and the Bell Comm report on "An Integrated Program of Space Utilization and Exploration for the Decade 1970 to 1980" (Reference [2]). Figure 1 shows a plan for the U. S. Space Program for the 1970-1990 period (Reference [2]). The funding level granted to NASA by Congress in fiscal years 1971 and 1972 indicate that this plan will not develop as rapidly as shown in Figure 1. More recent planning would seem to make the space shuttle the primary launch vehicle for future missions, and to give it the highest priority in development (References [3] and [4]). The other vehicles of the program such as the space station and the nuclear tug (which is used with the synchronous satellite and with lunar exploration efforts) are currently assigned a lower development priority.

Because of the considerable uncertainty in the direction and sequencing of the space program in the future, an attempt was made to establish guidelines and constraints which cover a broad spectrum of potential programs. This is particularly significant in the establishment of mission duration. Very long duration missions are considered relative to the current outlook for the space program for the next two decades. An ambitious program involving a substantial amount of EVA has been assumed as the upper extreme because, if the manned space program is to continue, man must be capable of performing useful work in space and on the planetary bodies, and undoubtedly, much of that work must be accomplished outside of the primary vehicle or base (Reference [5]).

3.1 Specification

The specification for the AEPS is given in Table I (it is taken from Reference [6], the NASA-Ames AEPS statement of work). This specification was not regarded as being inviolable, but was considered to be a guideline for use except where it was possible to demonstrate that a significant advantage could be gained by modifying it.

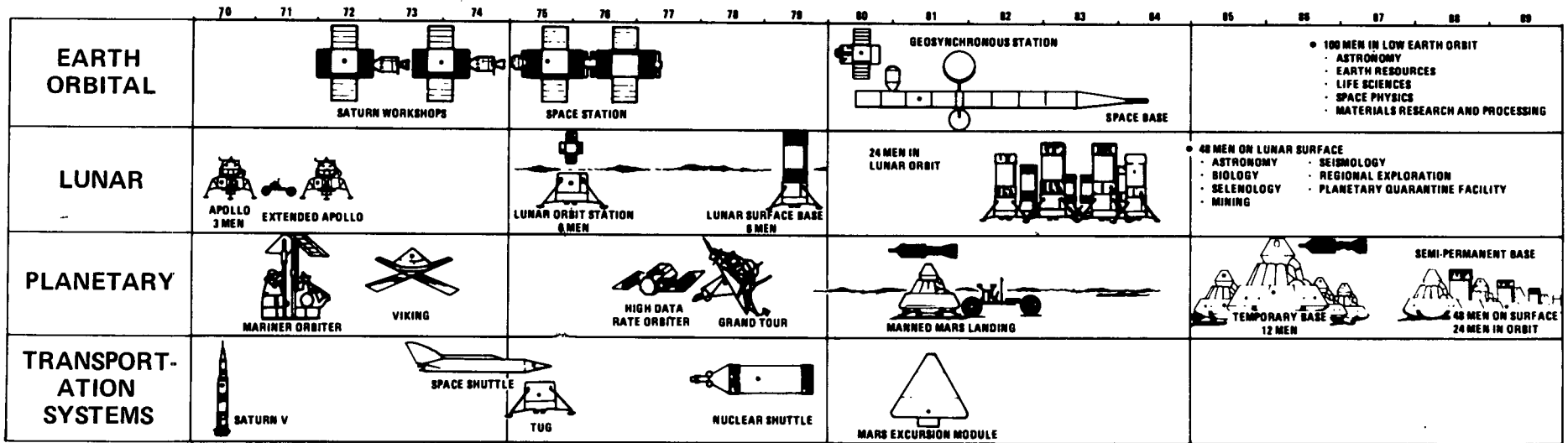


FIGURE 1 INTEGRATED SPACE PROGRAM 1970-1990 (REFERENCE 1)

EVA DURATION (AT AVERAGE METABOLIC RATE)	8 + HOURS	CONTAMINATION CONTROL a. NOMINAL INLET TO SUIT CO ₂ LEVEL b. MAXIMUM INLET CO ₂ LEVEL c. ODOR LEVEL	4 MM Hg (NO MIXING IN FACE REGION) 7.5 MM Hg MUST NOT ADVERSELY AFFECT CREWMAN PERFORMANCE
FREQUENCY OF MISSIONS	1 PER DAY		
MOBILITY	AEPS SHALL PROVIDE MINIMUM ENCUMBRANCE TO THE CREWMAN IN PERFORMANCE OF MISSION TASKS.		
CENTER OF GRAVITY	CG OF THE EVA SUIT AND LIFE SUPPORT ELEMENTS ATTACHED TO OR INTEGRATED WITH THE SUIT SHALL NOT SHIFT MORE THAN ± 3 INCHES FROM THE CG OF THE NUDE CREWMAN.	METABOLIC PROFILE a. AVERAGE PER SORTIE b. PEAK (SUSTAINED) c. MINIMUM d. AVERAGE OVER ALL SORTIES	1600 BTU/HR 3500 BTU/HR 250 BTU/HR 1200 BTU/HR
SUIT GAS COMPOSITION	3.7 – 7.5 PSIA PURE OXYGEN	LIQUID TRANSPORT LOOP FLOW	4 LB/MIN.
HUMIDITY CONTROL a. NOMINAL SUIT INLET DEW POINT b. MAXIMAL SUIT INLET DEW POINT	45°F 60°F	LIQUID INLET TEMPERATURE TO SUIT	40°F
		USE WITH VEHICLE OR SHELTER HAVING:	(a) 10 – 14.7 PSIA CABIN PRESSURE (b) 2.7 PSIA OXYGEN WITH DILUENT NITROGEN (c) RELATIVE HUMIDITY 55±5% (d) 65 – 75°F TEMPERATURE
VENTILATION (MINIMAL) a. INLET FLOW RATE b. INLET GAS TEMPERATURE c. SUIT LEAKAGE	9 ACFM 50 – 70°F 180 SCCM	SAFETY	THE SYSTEM SHALL PRECLUDE INJURY TO CREWMAN, SERVICE PERSONNEL, ETC., BECAUSE OF FIRE, EXPLOSION, TOXICITY, CONTAMINATION, AND BURNS OR SHOCK.
		OPERATIONAL ENVIRONMENTS	ZERO g, 1/6 g, 0.37 g and 1 g
		DONNING, DOFFING & CHECK-OUT TIME	MINIMIZE

TABLE I AEPS SPECIFICATION

3.2 Missions

The missions included in this study involved EVA operations in earth orbit, on the lunar surface, and on Mars. These missions are not well defined at this time, however, the parameters given in Table II (References [1], [2], and [7]) were adopted as a guideline.

	NUMBER OF CREWMAN	NUMBER OF TWO-MAN SORTIES	MISSION DURATION	RESUPPLY INTERVAL
EARTH ORBIT	6 TO 50	UP TO 500	1 YEAR	6 MONTHS
LUNAR SURFACE	6 TO 12	UP TO 500	1 YEAR	NONE
MARS SURFACE	6 TO 12	UP TO 500	UP TO 550 DAYS REF. (7)	NONE

TABLE II MISSIONS USING AEPS

In general, it was assumed that a minimum of two men would participate in each sortie, and the number of EVA sorties on a mission was taken to be a study variable with an upper limit of 500 two-man sorties. The specification calls for one sortie per day, so the study baselines the support equipment to meet this requirement; however, less frequent EVA events are also considered. This is significant to the heat rejection system, which is sensitive to the external thermal environment, which varies considerably on the lunar surface and also influences the base penalties required for power, heating, cooling, etc.

3.3 Primary Vehicle or Shelter

It was assumed that the EVA sorties are performed out of a primary vehicle or shelter which contains a closed atmosphere supply system. The exact nature of the carbon dioxide collection and reduction equipment was not specified; however, it was assumed that this equipment was sized large enough to accommodate the carbon dioxide which might be released during regeneration of the carbon dioxide sorbent used in the AEPS. It was assumed that this capability was provided in the primary vehicle or shelter. The capacity of this base O₂ reclamation system must be increased because the average metabolic rate of a crewman is 2-3 times greater during an EVA than it is at the base. Therefore, the crewman generates more CO₂ during the 8 hours of EVA than he would if he remained at the base.

The atmosphere in the primary vehicle or shelter was assumed to be comprised of the proper proportions of oxygen and nitrogen at a pressure of 10 psia to 14.7 psia, as required in the specification. It was assumed that the AEPS uses a 5 psia, pure oxygen atmosphere, after preliminary evaluation of a two-gas system. Therefore, it was necessary to assume that the primary vehicle or shelter contains a decompression/denitrogenation chamber which is suitable for egress and ingress of the AEPS users. It was assumed that this chamber can recover most of the atmosphere as it is depressurized. The requirements for this facility were essentially the same for all AEPS concepts considered, so the penalty for this facility was not considered in comparison of the various concepts.

It was assumed that electrical power, process heat, and process cooling were available for use in regeneration of AEPS components. The penalties (References [12] and [47]) assumed for these services are given in Table III.

	LB/KW
POWER PENALTY	500
PROCESS HEAT* (UP TO 300°F)	100
PROCESS COOLING* (DOWN TO 40°F)	50

NOTE:

*EQUIPMENT FOR INCREASED TEMPERATURE RANGE IS EVALUATED SEPARATELY.

POWER SYSTEMS VOLUME PENALTY 40 LB/FT³ OR 0.025 FT³/LB OR 125 FT³/KW.

TABLE III MAIN VEHICLE OR SHELTER ENERGY PENALTIES

The same penalty factors are used for all missions, although it is recognized that the exact penalty would depend on the nature of the mission, and the time frame in which it is carried out. The penalties are considered to be representative nominal values, and to be realistic for use in a study such as this.

3.4 Astronaut Locomotion and Mobility

An astronaut requires some means of locomotion in order to function effectively in an EVA. In an orbital environment there is no means of locomotion naturally available (like walking on earth) so some provisions must be made to enhance mobility. In most instances the distances which must be traversed are small. The means available are:

- (1) Handholds on the vehicle (probably with a tether)
- (2) Astronaut maneuvering unit (with or without a tether)
- (3) Maneuvering Work Platform or Space Taxi (a small one-man vehicle)

Any one or all of these techniques could eventually be used in space. For this study the first two possibilities are considered. The third alternative could support activity of the first two types, and might well include a closed cabin and sophisticated life support system; for this reason it is not considered in this study.

On planetary surfaces the locomotion techniques available to the crewman are:

- (1) Walk
- (2) Walk supported by an equipment transporter similar to the Modular Equipment Transporter (MET)
- (3) Ride a small powered vehicle such as the Lunar Rover planned for use on Apollo 15, 16, and 17

The crewman can walk about freely, as was witnessed on the Apollo 11, 12 and 14 flights; however, the range which can be covered by a man walking in a space suit over rugged terrain, with no paths or trails, is very limited. For this reason, it was assumed that the astronaut would not operate at a distance of more than a one-hour walk from a support vehicle of some sort. The support vehicle might take the form of a cart, such as the Modular Equipment Transporter (MET) used on the Apollo 14 mission, or it might be a powered vehicle, such as the lunar rover which is currently planned for use on Apollo missions 15, 16, and 17. Support might also be provided by a larger powered vehicle which could contain a relatively sophisticated life support system.

There are two fundamentally different methods of carrying out life support functions with the aid of a supporting vehicle. They are to connect the crewman to the vehicle by means of a part or full-time umbilical, or to carry replaceable modules that can be used during the EVA. The simplest form of umbilical is one that supplies electric power only. A liquid cooling umbilical would be slightly larger and more restrictive, while a gas umbilical is the largest and most difficult to use. Both the umbilical and modular methods were considered and it was found that the choice of which is superior can only be made at the detailed mission planning stage.

The umbilical restricts the EVA mobility for some operations but this may not be a handicap for activities such as driving a rover, etc. However, it was decided that any umbilical system must retain the capability to operate without the umbilical, since this may be required for some missions. The optimum systems used for non-umbilical operation might use expendables, since proper EVA planning would minimize the time they would be used.

The modular approach does not impose a mobility restriction during normal operation. It is assumed that the crewman can return to his support cart at convenient intervals (every 1-2 hours) and replace spent modules with fresh ones. This would allow concepts such as fusible heat sinks, which might be too large to carry conveniently, to be split into more easily manageable segments. However, this approach does consume EVA time for replacement of the modules and there is a potential reliability problem in the replacement mechanism. It was assumed that any modular system must retain the capability to operate without the support modules for missions where this may be required. This operation can be done with a penalty in expendables. The modular approach has the advantage that the EVA weight can be optimized for different duration EVA's, by only carrying a sufficient number of modules to satisfy the desired EVA duration.

For purposes of this study, the AEPS life support system is assumed to be limited to the MET and powered "rover" type of vehicles. The larger powered vehicle life support system is not considered in this study.

The mobility of the astronaut is primarily governed by the local gravitational force, the suit mobility, and the mass, volume and center of gravity (c.g.) of the equipment carried by the man. No control can be exercised over the local gravitational force, and the specification establishes the space suit mobility as being similar to the Apollo A7L suit so that weight, volume and c.g. of the portable equipment are the only mobility parameters over which this study has any influence. The specification limits c.g. shift of the crewman to less than ± 3 inches. This requirement is difficult to apply to a study of subsystem operational concepts; however, an attempt was made to insure that concepts considered could reasonably be expected to result in a final hardware configuration that would satisfy this constraint. The mass and volume limitations assumed for the life support system by the crewman or on the support equipment are given in Table IV.

TRANSPORT TECHNIQUE	MASS LB.	VOLUME IN ³
BACKPACK AND/OR CHEST PACK*	200	8600
"MET" TYPE TRANSPORTER	200	8600
"ROVER" TYPE POWERED VEHICLE	1000	40,000

*BASED ON THE LTV AEROSPACE/USAF ASTRONAUT MANEUVERING UNIT (AMU)

TABLE IV MAXIMUM MASS AND VOLUME REQUIREMENTS

The assumed maximum allowable mass and volume to be carried by the crewman were deliberately chosen on the high side, to reduce the likelihood that an otherwise attractive subsystem concept would be eliminated from consideration because of excessive mass or volume requirements. The assumption is made that detailed integration of an AEPS could be arranged in such a way as to accommodate attractive subsystems, through reduction in mission capability, selection of other subsystems, and/or improved packaging techniques.

3.5 Design Environments

The design environments for AEPS are given in Table V.

	EARTH ORBIT	*LUNAR SURFACE	**MARS SURFACE
SOLAR FLUX (BTU/HR FT ²)	442	442	164 TO 240
ALBEDO	0.35	0.07	0.17
EQUIV. SURFACE TEMP (°R)	453	170 – 760	POLE: 140 – 470 EQUATOR: 310 – 590
MEAN GRAV. CONSTANT (g)	–	0.17	0.38
ROTATIONAL PERIOD (HRS)	–	655	24.61
ATMOS. PRESSURE (MB)	–	–	6

*REFERENCE (21)

**REFERENCES (22) AND (23)

TABLE V AEPS DESIGN ENVIRONMENTS

In this study it was assumed that the AEPS design could be optimized for each individual operating environment if this was found to be advantageous. This is a departure from the philosophy which guided the Apollo PLSS, which

required the unit to be operational in either an orbital (zero-g) environment, or a lunar surface environment.

A brief study of the thermal environments for AEPS was made so that the heat leak into the AEPS from the external environment could be assessed. For earth orbit and on the lunar surface it was assumed that the AEPS space suit was similar to the Apollo A7L suit although the influence of system heat leak on the heat rejection system was considered.

The Mars surface has a significant atmospheric pressure (References [22] and [23]) and has high velocity winds at times so that the convective heat transfer produced by these winds must be considered. The atmospheric pressure on Mars is large enough to greatly increase the thermal conductivity across an Apollo type suit, and thus to increase the heat transfer through the suit. The environment on Mars is relatively low in temperature, so this increased conductivity is primarily manifested in an increase in heat loss through the suit. Increasing the heat loss from the suit is beneficial since it reduces the heat load on the primary heat rejection system. The heat loss or gain through the AEPS space suit and support equipment used in the study is given on Figure 2. The values for lunar operation are variable with sun angle; however, for earth orbit and the Mars surface average values have been used for simplicity. There are potential thermal problems with hot and/or cold spots inside the suit; however, these problems were not considered in this study.

The design conditions used for radiator surfaces were as follows: for earth orbit, earth emission, earth albedo, and direct solar radiation were considered; for the lunar surface and for the Mars surface the most severe radiation environment was considered to be the planetary equator. It was found that optical solar reflector (OSR) radiator coatings ($\alpha = 0.1$, $\epsilon = 0.9$) would be required for lunar operation of a simple, upward facing radiator. Directional, shielded radiators that would minimize environmental heating were also considered but the size was found to be prohibitive for a portable system. A Mars radiator system could use conventional ($\alpha = 0.3$) coatings due to the lower sink temperature. No attempt was made to assess the impact of planetary dust on the radiator coating optical properties, although this is recognized as a potential problem area.

3.6 Heat Load

The sources of heat load on the AEPS are:

- (1) Crewman metabolic heat
- (2) Reactions in the life support system
- (3) Suit Heat Leak
- (4) Electronic equipment

The crewman is the largest source of heat in the AEPS; the crewman generated heat can range from a basic metabolism rate of around 250 BTU/hr up to the range of 40,000 BTU/hr for short periods (Reference [24]),

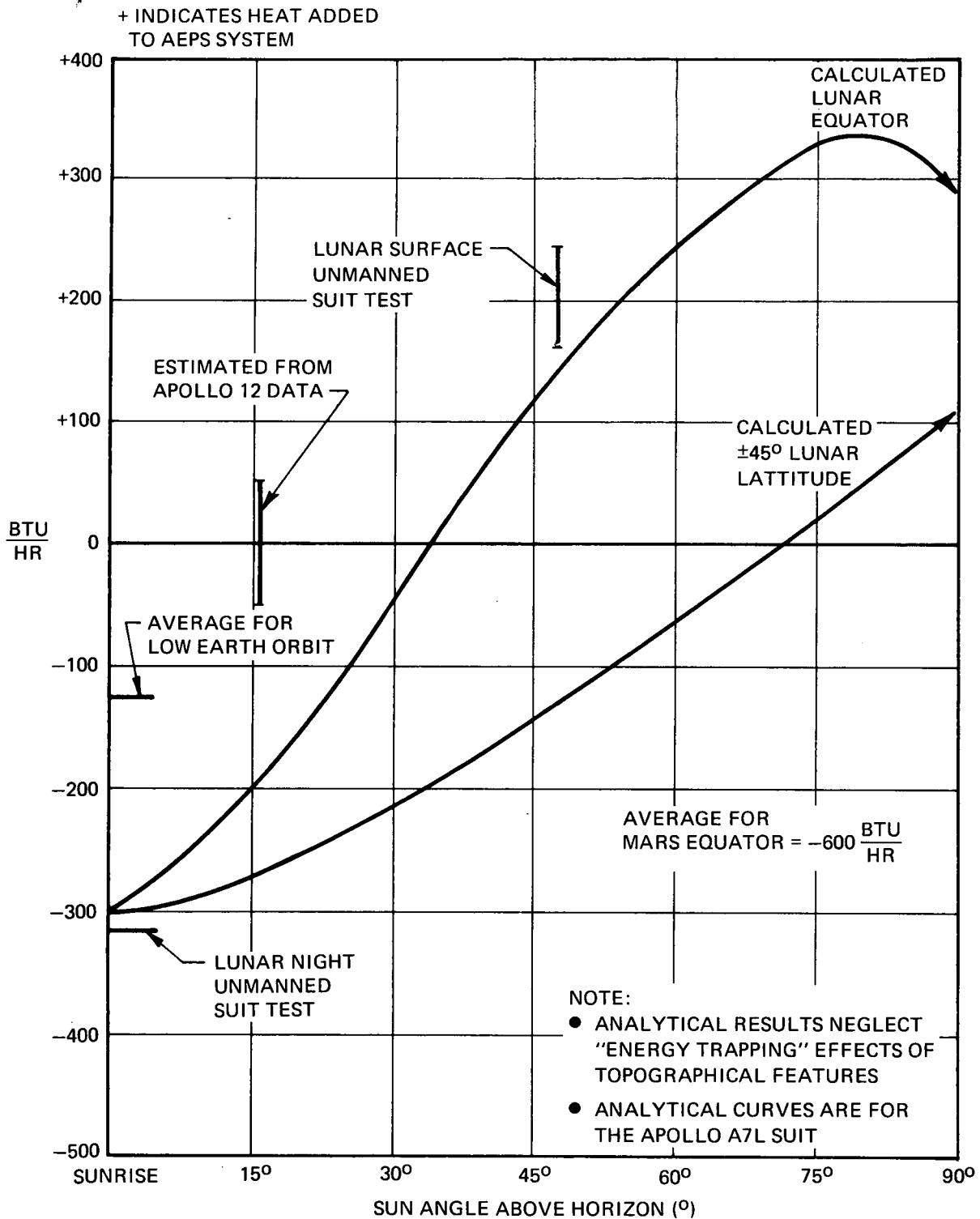
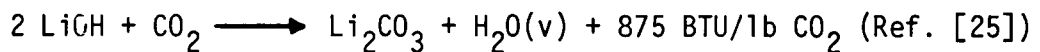


FIGURE 2 AEPS SUIT AND BACKPACK HEAT LEAK

such as for a man running 100 yards in 10 seconds. The highest measured daily (24 hour) average is about 1300 BTU/hr (Reference [24]). The AEPS specification calls for a minimum of 250 BTU/hr, an average per sortie of 1600 BTU/hr, and a short-term peak of 3500 BTU/hr.

The crewman performs useful work during EVA; however, a large part of his effort is expended in bending the space suit. Only a fraction of the energy expended by the crewman results in work performed on exterior bodies. For this study, it has been assumed that the crewman performs at an efficiency of 8% on the basis of work done external to the control volume comprised of the crewman, his suit, and his life support equipment. Typical overall efficiencies are from 5 to 35% (Reference [24]). That portion of the crewman's effort which goes into work in the suit, which is useful work above 8% of the metabolic rate (MR), is assumed to be converted into frictional heat inside of the control volume. The metabolic heat release inside the control volume is then 92% of the metabolic rate.

Most of the CO₂ control processes which could be used in AEPS produce heat as the CO₂ is removed from the suit atmosphere. This heat is released in the AEPS control volume. For the evaluation of AEPS heat rejection systems, the LiOH heat of reaction in removing CO₂ has been assumed. The equation for this reaction is



The water vapor released by this reaction (0.409 lb/lb of CO₂) must be removed in the humidity control system (which requires 438 BTU/lb of CO₂, for simple condensation) so the total heat release is 1313 BTU/lb of CO₂. The CO₂ removal rate can be related to the metabolic rate as follows: for a respiratory quotient of 0.82, the metabolic rate is 4.825 KCal per liter of oxygen consumed (Reference [24]). This is a production of 6081.6 BTU per lb of O₂ consumed, or for a respiratory quotient of 0.82; 5393.7 BTU per lb of CO₂ produced. Thus the ratio of heat release in CO₂ removal to metabolic heat is

$$\text{Ratio} = \frac{1313 \text{ BTU/lb of CO}_2 \text{ reacted}}{5393.7 \text{ BTU/lb of CO}_2 \text{ produced}} = 0.2434$$

For this study, then, the baseline used to evaluate heat rejection systems assumes that an amount of energy equal to 24% of the metabolic rate is released in the AEPS carbon dioxide control system.

The heat lost or gained through the suit and the AEPS equipment is given on Figure 2, as discussed previously.

Electrical and electronic equipment heat release was baselined as 50 BTU/hr, a figure similar to that experienced with the Apollo PLSS. This includes the communications equipment, the battery losses, the line losses, the liquid-cooled garment (LCG) pump, and the ventilation fan.

The equation for AEPS heat load is then:

$$\text{Heat Load} = \text{Metabolic Rate (MR)} - \text{Useful Work} + \text{CO}_2$$

reaction heat release \pm suit heat leak + electrical equipment heat release

$$= \text{MR} - 0.08 \text{ MR} + 0.24 \text{ MR} + \text{Heat Leak} \\ (\text{from Figure 2}) + 50 \text{ BTU/hr}$$

$$= 1.16 \text{ MR} \pm \text{Heat Leak (Figure 2)} + 50 \text{ BTU/hr}$$

This equation has been plotted parametrically on Figure 3, so that the AEPS heat load can be read directly from metabolic rate and suit heat leak. The heat rejection system is required to maintain the atmosphere temperature at 65 to 75°F and at a dew point of 45 to 60°F at the inlet to the suit. The specification also requires that the LCG inlet water temperature be as low as 40°F; however, in this study it has been assumed that an improved LCG can be utilized which will allow an inlet temperature of 70°F at the maximum sustained metabolic rate. This assumption allows consideration of some heat rejection techniques which would be impractical if the LCG inlet temperature always had to be 40°F.

3.7 AEPS Contaminants

The contaminants that must be removed by the AEPS system are primarily products of the crewman's biological processes. The primary contaminants are CO₂, water vapor, and trace gases. All of these substances are produced at sufficiently high rates that they must be removed from the AEPS volume during the course of an EVA. The AEPS subsystems required to maintain these substances within the specifications detailed in Table I will be discussed in Sections 4.2, 4.3, and 4.5.

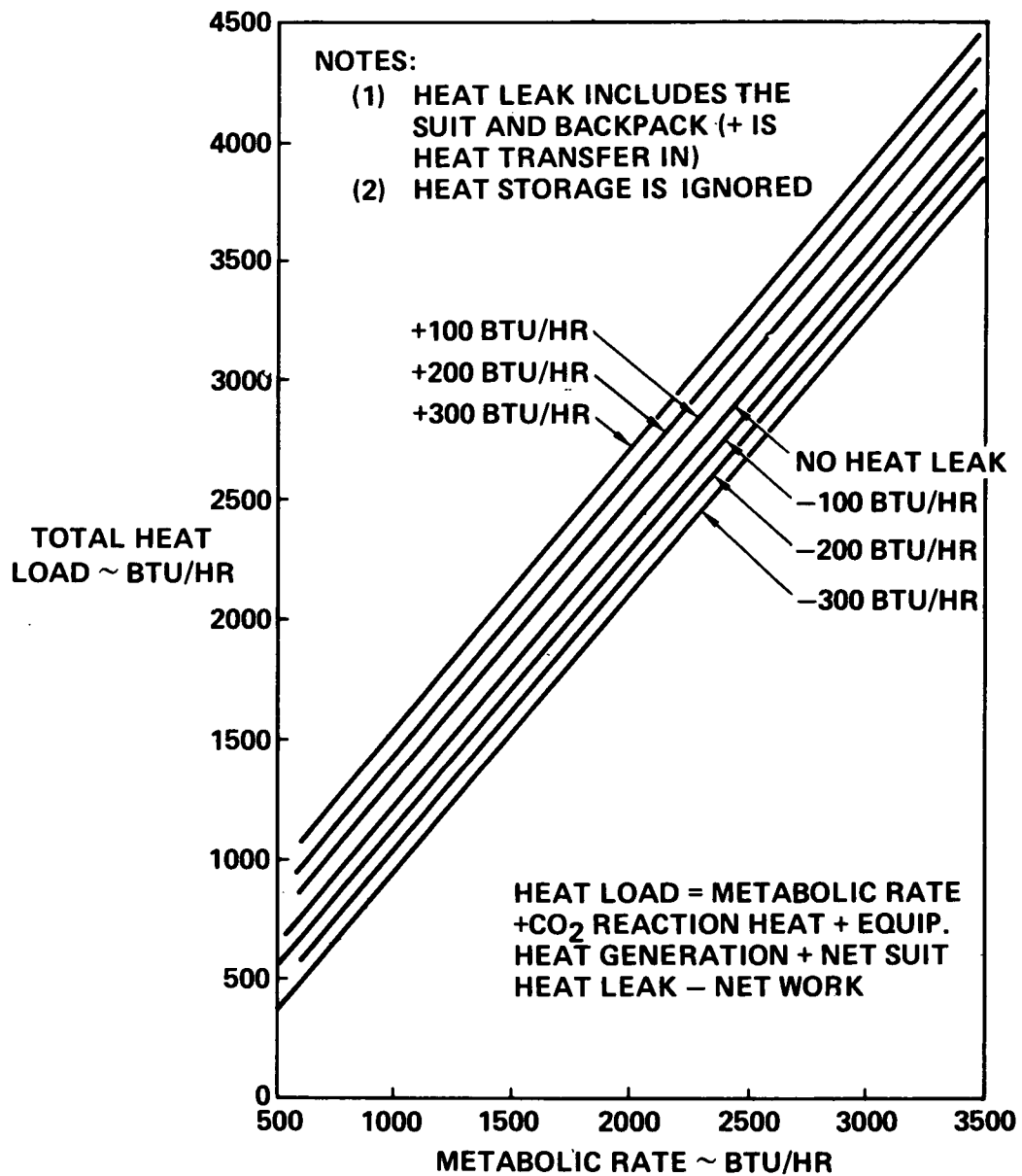


FIGURE 3 ADVANCED EXTRAVEHICULAR PROTECTIVE SYSTEM TOTAL HEAT LOAD

4.0 SUBSYSTEM CONCEPT GENERATION AND ANALYSIS

The life support function subsystems required in an AEPS are shown in the schematic on Figure 4. The depicted arrangement of subsystems in the flow systems is workable; although it is not necessarily optimum for all possible combinations of subsystems. This section discusses the generation of concepts for the subsystems, and the analysis of those subsystems to establish reasonable weights, volumes, operating characteristics, etc. for use in overall system evaluation. The subsystems considered are:

- (1) Atmosphere supply
- (2) Carbon dioxide control
- (3) Trace contaminant control
- (4) Thermal control
- (5) Humidity control
- (6) Power supply

It is possible that a food and drink supply system and some type of waste management system will be required for a man in an AEPS with an 8-hour sortie duration; however, these systems were not considered in this study. New concepts for components such as fans, pumps, valves, etc. were not investigated because the likelihood of substantial improvement in these components is remote. The power supply is included in the study because of the possibility of integration of the power supply with other subsystems, and because there is a high probability that a significant improvement in power systems can be made in the next decade.

4.1 Atmosphere Supply Subsystem

The atmosphere for AEPS was specified as pure oxygen at a pressure of 3.7 to 7.5 psia. The use of a two-gas atmosphere system would reduce the preparation time for EVA, since an oxygen conditioning period to reduce the nitrogen content in the crewman's body, would not be required. This would also simplify the design and reduce the weight of the parent vehicle or shelter since the oxygen pre-conditioning equipment would be eliminated. However, the two-gas atmosphere requires higher suit pressures, and greatly increases the risk associated with rapid decompression in the event of a suit gas leak. Some investigation was made into the use of two-gas suits; however, most of the effort concerned only the pure oxygen suit atmosphere.

4.1.1 Candidate Subsystem Concepts

In selection of the atmosphere supply subsystem for AEPS it was assumed that a closed circulation system would result, that is, that the atmosphere supply subsystem must only make up suit leakage and metabolic oxygen consumption. The various methods of providing the atmosphere for AEPS which were considered in this study are listed in Table VI. The basic techniques considered included elemental oxygen storage, chemical storage, and regeneration of oxygen from carbon dioxide. Table VI shows the results of the preliminary analyses on oxygen supply systems. The regeneration of oxygen from carbon dioxide interfaces with the carbon dioxide control system which is discussed in Section 4.2. However, except

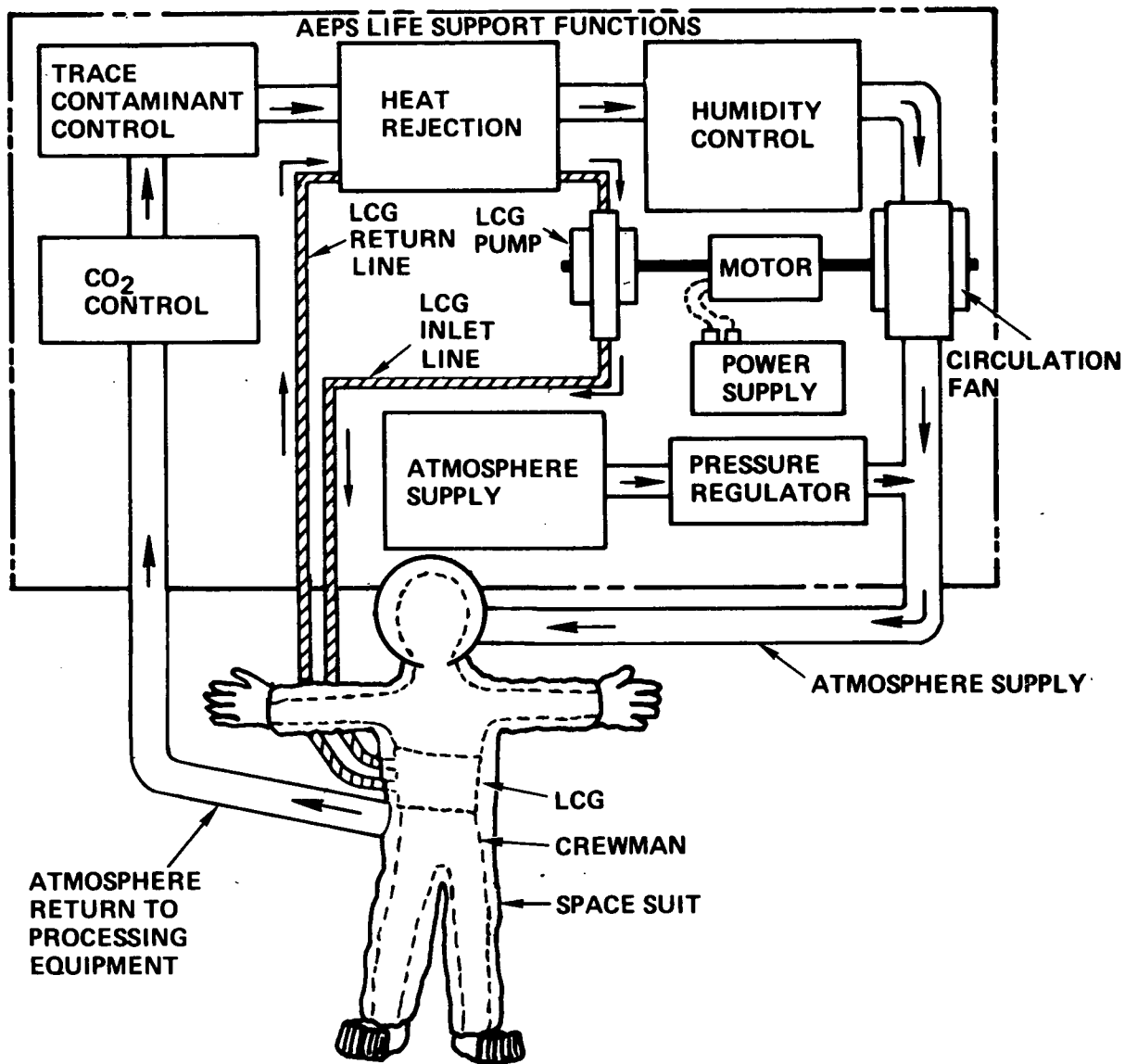


FIGURE 4 AEPS LIFE SUPPORT SYSTEM SCHEMATIC

SUPPLY OR STORAGE TECHNIQUE	5000 PSI GAS	SUPER-CRITICAL	SUB-CRITICAL	WATER ELEC-TROLYSIS	HYDRO-GEN PEROXIDE	CHLO-RATES & PERCHLO-RATES	SUPER-OXIDES, OZANIDES	BOSCH REACTOR	SABA-TIER REACTOR	SOLID ELECTRO-LYTE	FUSED SALT
EVA WEIGHT $\frac{LB_m}{LB_m O_2}$	3	1.5	1.2	11	2.5	LARGE	2.5	LARGE	LARGE	LARGE	LARGE
EVA VOLUME	LOW	VERY LOW	VERY LOW	MEDIUM	MEDIUM	LOW	LOW	HIGH	HIGH	HIGH	HIGH
EVA RELIABILITY	HIGH	HIGH	HIGH	LOW	MEDIUM	MEDIUM	MEDIUM	LOW	LOW	LOW	LOW

TABLE VI CANDIDATE OXYGEN SUPPLY SYSTEMS

for the fused salt system, a carbon dioxide system is required in addition to the oxygen generation device. All of these CO₂ reduction/O₂ generation systems are large in weight, have large power requirements, and are relatively complex. These factors, coupled with the availability of more suitable approaches, makes the EVA regeneration of oxygen from carbon dioxide in an AEPS an unrealistic approach.

There are some chemical systems which react with carbon dioxide to form oxygen; however, there is a problem in regulation of the oxygen production to match demand in a space suit. This requires a supplemental oxygen supply, particularly if emergency conditions are considered. Table VII gives a comparison of the candidate chemical oxygen supply techniques.

The primary vehicle or shelter oxygen supply system has some impact on the AEPS; and it should not be selected without consideration of this interface. The use of high pressure gas storage in AEPS creates a requirement for an oxygen compressor in the primary vehicle or shelter. This approach is compatible with any probable primary vehicle or shelter oxygen supply system. In many possible AEPS designs, the requirement for EVA oxygen will greatly exceed the primary vehicle or shelter make-up oxygen requirement, and the addition of the EVA oxygen to the make-up oxygen supply may have a significant influence on the selection of the primary vehicle or shelter oxygen storage technique.

In addition to the usual methods of storing oxygen, which were discussed in the preceding paragraphs, there are two additional oxygen supply sources which will have to be considered for the primary vehicle or shelter. These are:

(1) If frozen food is used extensively on future missions, in lieu of freeze-dried foods, then a considerable amount of water will be available from the waste water recovery system after the food is consumed and digested by the crew (Reference [26]). This water can be electrolyzed to generate oxygen.

STORAGE METHOD	AVAILABLE O ₂ (THEORETICAL), WEIGHT %	PURITY	AVAILABLE O ₂ , LB/LB	DENSITY, LB/CU IN	HEAT OF REACTION, BTU/LB ⁽²⁾	O ₂ DENSITY, LB/CU IN
KO ₂	33.8	—	0.32	0.0237	415 ⁽³⁾	0.0076
NaO ₂	43.6	0.90	0.392	—	635 ⁽⁴⁾	(0.009)
Li ₂ O ₂	34.8	(1)	0.375	0.0074	-363 ⁽⁵⁾	0.029 to 0.006
NaO ₃	56.3	—	—	—	+1515	—
LiNO ₃	23.2	1.00	0.232	0.0861	-488	0.020
LiClO ₄	60.1	1.00	0.601	0.0878	-596	0.053
NaClO ₃	45.1	—	0.40	0.0815	+422	0.032
90% H ₂ O ₂	47.1	0.90	0.423	0.0502	+1106	0.021
98% H ₂ O ₂	47.1	0.98	0.461	0.0515	1214	0.026 ⁽⁶⁾
HIGH PRESSURE STORAGE OF O ₂	100	0.99+	0.33 ⁽⁶⁾	(1000 PSIA) 0.0026 to (10,000 PSIA) 0.019	-50	0.0026 to 0.019

(1) 10 PERCENT Li₂O₄

(2) + INDICATES EXOTHERMIC REACTIONS; - INDICATES ENDOTHERMIC REACTION

(3) $2 \text{ KO}_2 + 1.23 \text{ CO}_2 + 0.23 \text{ H}_2\text{O} = 0.77 \text{ K}_2\text{CO}_3 + 0.46 \text{ KHCO}_3 + 1.5 \text{ O}_2$

(4) $2 \text{ NaO}_2 + 1.23 \text{ CO}_2 + 0.23 \text{ H}_2\text{O} = 0.77 \text{ Na}_2\text{CO}_3 + 0.46 \text{ NaHCO}_3 + 1.5 \text{ O}_2$

(5) $\text{Li}_2\text{O}_2 = \text{Li}_2\text{O} + 1/2 \text{ O}_2$

(6) INCLUDING STORAGE TANK

(7) EXCLUDING STORAGE OR CONTAINING VESSEL, EXCEPT AS NOTED

TABLE VII COMPARISONS OF CANDIDATE OXYGEN SUPPLY TECHNIQUES

(2) Water can be generated from the lunar soil (and probably from Martian soil) (References [27] - [30]); and that water can be electrolyzed to generate oxygen. The most likely reason for establishing such a process plant would be for production of oxygen for use in propulsion systems.

If either of the above systems were selected for use in a future mission, it might reduce the cost of oxygen (that is, greatly increase the availability), and this could have an impact on subsystem selection for AEPS.

4.1.2 Recommended Subsystem Concept

It was concluded that high pressure (approximately 5000 psia) gaseous oxygen storage is the optimum method for AEPS. This method combines low EVA weight and volume with maximum reliability and ease of integration with base systems. It is compatible with any base system since a compressor can be used to fill the EVA tanks directly from the base atmosphere if desired. The construction of a 5000 psia tank, pressure regulator, and compressor, is well within present technology and improvements in materials, etc., will further reduce the tank weight and volume.

A detailed sizing analysis was performed on the oxygen supply tank. The tank is assumed to be spherical, constructed of stainless steel, and contains 2.76 lb_m of oxygen. The tank weighs 10.5 lb_m including mounts, etc., and occupies 213 cu. in. Stainless steel construction was chosen over more exotic techniques because the tank must have a long cycle life, and must not be readily susceptible to stress corrosion, hydrogen embrittlement, or similar problems which can occur when exacting cleanliness procedures cannot be carefully observed. The tank includes an inner shell that functions as a regenerative heat exchanger which insures heat transfer from the tank to the oxygen during rapid gas expulsion in a zero-gravity environment. This regenerator will not be required for many possible system designs.

4.2 Carbon Dioxide Control

As previously mentioned in Section 4.1, the basic assumption was made that AEPS would have a closed atmosphere, and thus that carbon dioxide must be removed from the system at a rate proportional to the metabolic rate (since the system volume is too small to provide a significant "damping" effect). The alternative to this is an open atmospheric system in which carbon dioxide control is achieved by venting a substantial amount of the atmospheric gas overboard; this system has been used in EVA equipment such as the Astronaut Maneuvering Unit where about 1/4 of the total system flowrate was vented overboard (Reference [31]). This requires about 20 times as much oxygen as the basic suit leakage and metabolic requirements. A more recent open system has been developed (Reference [32]). This system uses a breathing vest with a face mask device, and delivers oxygen at the rate it is drawn into the lungs; (approximately 1.8 lb/hr for a metabolic rate of 1600 BTU/hr and a suit pressure of 5 psia). This would then require an expendable weight of 14.4 lb on the AEPS design mission.

In this study, as previously noted, it has been assumed that large quantities of oxygen are not readily available, and thus that a regenerable closed-system is required.

There were three levels of regeneration which were considered:

(1) A completely EVA regenerable system in which the carbon dioxide is separated from the AEPS atmosphere, and is reduced to generate oxygen.

(2) A partially regenerable system in which the carbon dioxide sorbent is regenerated, and the carbon dioxide is vented overboard (and the oxygen chemically combined with carbon is thus lost).

(3) A completely regenerable system in which the carbon dioxide sorbent is regenerated at the parent vehicle or shelter where the carbon dioxide is recovered and is reduced in the parent vehicle life support equipment.

In addition to these regenerable systems, completely expendable systems were also considered.

4.2.1 Carbon Dioxide Levels

One of the most significant factors in designing a carbon dioxide control system for a space suit application, is the allowable carbon dioxide partial pressure. Early suit design set the nominal level at 7.5 mm Hg in the helmet area. This helmet carbon dioxide partial pressure level is influenced by the helmet design (which influences the ventilation of the expired gas from the oral-nasal region), and the inlet gas carbon dioxide partial pressure. The AEPS specification calls for an inlet carbon dioxide partial pressure of 4 mm Hg, and assumes that the helmet design provides adequate ventilation to make that inlet gas carbon dioxide partial pressure acceptable. Because of the controversy surrounding the carbon dioxide pressure level, an inlet partial pressure of 2 mm Hg has been used where the technique being considered could provide it, without significant penalty.

The metabolic rate is very significant in sizing the carbon dioxide control system, both from the standpoint of average metabolic rate and maximum metabolic rate, since the rate of CO₂ production is proportional to the metabolic rate and the respiratory quotient.

The respiratory quotient, R.Q., (i.e., volume of CO₂ exhaled/ volume of O₂ inhaled) is an indicator of the efficiency of the respiratory and other metabolic processes. Thus, it varies both between individuals and within a given individual as a function of diet and general health. An R.Q. of 0.875 has been recommended for astronauts (Reference [47]), but values ranging from 0.7 to 1.0 have been determined experimentally for a wide range of subjects. A value of 0.97 was assumed for AEPS CO₂ calculations to insure a conservative evaluation of all data. The CO₂ production rate is then found to be

0.75 lb_m/hr (Reference [24]) at a metabolic rate of 3500 BTU/hr and 0.35 lb_m/hr at 1600 BTU/hr. At the total mission average metabolic rate of 1200 BTU/hr, 0.255 lb_mCO₂/hr are produced. Since the volume of the space suit is relatively small (on the order of 2 cu. ft., or enough volume to contain only 0.0006 lb of CO₂ at a partial pressure of 4 mm Hg), the carbon dioxide control system must be sized to remove carbon dioxide at the maximum instantaneous production rate.

The penalty for the oxygen required for an EVA is assigned to the CO₂ control system since, with the assumption of a closed gas circulation system, the bulk of the oxygen required is converted to CO₂. For those systems that collect the CO₂ during the EVA and return it to the base in any chemical form (i.e., carbonates, gaseous CO₂, etc.) an increase in the size of the base CO₂ reduction system/O₂ production system of 500 lb_m and 12.5 ft³ was assigned as a penalty (see Section 3.3). A further base penalty was assigned to convert the CO₂ to the gaseous state if this was required.

4.2.2 Gas Separation Ratio

In order to separate two gases, such as oxygen and carbon dioxide, advantage must be taken of some difference in the physical and/or chemical properties of the two gases. In this instance there is a requirement to reduce the carbon dioxide partial pressure down to 2 mm Hg while the total pressure is approximately 5 psia. The partial pressure ratio of the two gases is then:

$$\frac{P_{CO_2}}{P_{O_2}} = \frac{2 \text{ mm Hg}}{5 \text{ psia}} = \frac{1}{125}$$

The partial pressure ratio represents the ratio of the quantities of each gas present; and so the separation potential applied to the system must affect the carbon dioxide by at least a factor of 125 more than it affects oxygen, otherwise as much oxygen as carbon dioxide will be separated out. This would be particularly significant in the case of non-regenerable subsystems.

4.2.3 Recommended Subsystem Concepts

Table VIII shows the most promising CO₂ control methods that were considered for AEPS. Many other concepts were considered and rejected as being impractical for AEPS without performing a preliminary sizing and performance analysis. The systems that were eliminated by the preliminary analysis are shown, along with those that were considered in detail. This preliminary screening was used to reduce the number of systems which had to be compared by detailed analysis. Many concepts were discarded at this stage because of obvious problems with excessive size, prohibitive regeneration penalties, or because they did not offer any potential improvement over existing systems. Detailed analysis further reduced these candidates to four promising candidate subsystems:

METHOD	DETAILED ANALYSIS	PRELIMINARY ANALYSIS ONLY	COMMENTS
<u>CHEMICAL EXPENDABLE</u>			
• LiOH	X		GOOD FOR LIMITED NUMBER OF SORTIES
• KO ₂ , NaO ₂		X	NO ADVANTAGE OVER LiOH
• Li ₂ O ₂		X	NO ADVANTAGE OVER LiOH
<u>CHEMICAL, REGENERABLE</u>			
• LiOH	X		HIGH REGENERATION PENALTY
• KOH	X		MODERATE POWER FOR BASE REGENERATION
• KO ₂ , NaO ₂ , Li ₂ O ₂		X	EXCESSIVE POWER FOR BASE REGENERATION
• KO ₃		X	EXCESSIVE POWER FOR BASE REGENERATION
• Mg (OH) ₂	X		MODERATE TEMPERATURE FOR REGENERATION
• Ca (OH) ₂		X	EXCESSIVELY HIGH REGENERATION TEMPERATURE
<u>ADSORPTION</u>			
• DEAD END MOLE-SIEVES (ZEOLITE)		X	EXCESSIVE EVA MASS AND VOLUME
• VACUUM DESORBED MOLE SIEVES (ZEOLITE) CLASS B ONLY	X		GOOD FOR MODERATE NUMBER OF EVA'S, BUT HAS LARGE EVA MASS AND VOLUME
• VACUUM DESORBED ZEOLITE WITH LiOH "TOP-OFF" (CLASS A ONLY)	X		EXCESSIVELY LARGE EVA MASS WITHOUT ANY SIGNIFICANT REDUCTION IN EXPENDABLES
• NON-WATER SENSITIVE MOLE-SIEVES		X	NO ADVANTAGE OVER ZEOLITES
<u>ABSORPTION</u>			
• BATCH VACUUM DESORBED SOLID AMINES	X		LARGE EVA MASS SUITABLE FOR LIMITED NUMBER OF EVA'S
• LIQUID WATER SOLUTION OF AMINES VACUUM DESORBED		X	EXCESSIVE WATER LOSS DURING EVA
• LIQUID WATER SOLUTION OF CARBONATES WITH VACUUM DESORPTION		X	EXCESSIVE WATER LOSS
a. LIQUID LOOPS			
b. MEMBRANES			
• DEAD END WATER SOLUTION OF CARBONATES		X	EXCESSIVE EVA SIZE
<u>VACUUM VENT</u>			
• SIMPLE SYSTEM, NO UMBILICAL		X	EXCESSIVE EVA MASS AND EXPENDABLES
• 1.0 HR FREE FLIGHT WITH UMBILICAL TO PRIMARY BASE	X		SHOWS SOME PROMISE WHEN THE EVA MISSION DOES NOT REQUIRE LONG DURATIONS AT DISTANCES FROM THE SPACE BASE
<u>OTHER</u>			
• CONVERSION OF CO ₂ TO WATER BY A BOSCH REACTOR FOR RECOVERY OF O ₂ AT BASE		X	VERY HIGH EVA MASS
• H ₂ -DEPOLARIZED CARBONATION CELL, VACUUM VENT		X	LARGE SYSTEM SIZE, HIGH EXPENDABLES
• VACUUM VENTED SINGLE STAGE CARBONATION CELL		X	HIGH EVA SYSTEM MASS AND POWER, HIGH EXPENDABLES
• Cu/O ₂ FUEL CELL CO ₂ SORBER		X	LOW CONVERSION EFFICIENCY TO CARBONATE
• ANY SYSTEM CONCENTRATING CO ₂ & THEN RECOVERING O ₂ DURING THE EVA		X	EXTRAORDINARILY HIGH EVA MASS VOLUMES AND POWER PENALTIES

TABLE VIII CANDIDATE CO₂ CONTROL METHODS

- . LiOH (expendable)
- . Solid Amines (partially regenerable, i.e., the CO₂ is lost)
- . KOH (regenerable at the base)
- . Mg(OH)₂ (regenerable at the base)

LiOH is extremely reactive with CO₂ and the LiOH system is the lightest weight and most compact CO₂ control system available. LiOH is thus very satisfactory for missions where a relatively small number of EVA's are required. No other expendable CO₂ control method was found that would be competitive with LiOH from a weight and volume standpoint. It is possible to reverse the reaction and recover LiOH from the lithium carbonate (Li₂CO₃) produced during the EVA. However, considerable amounts of energy are required because Li₂CO₃ is relatively insoluble in water, making simple water electrolysis impractical and thermal regeneration is also not feasible. An axial flow canister was assumed that would increase the LiOH utilization efficiency from the present 35% to about 68%. The pressure drop is also increased but this is made up by slightly increasing the size of the regenerable power supply.

Solid amine systems are being researched for use as CO₂ concentrators in a primary base system. The most promising solid amine system for AEPS incorporates a vacuum-vent mode of operation. This system uses two beds in a cyclic fashion with one bed absorbing CO₂ from the gas stream while the other bed is desorbed to space. The system is classed as partially expendable because the CO₂ sorbent is reused but the CO₂, along with the water vapor and oxygen contained in the bed free volume, is vented to space. Solid amine CO₂ sorbents have a low capacity for CO₂ on a lb_m of CO₂ per lb_m sorbent basis when compared to chemicals such as LiOH, and they have a lower reaction rate. Thus, the required bed size is much larger than a LiOH bed. The amine bed acts as a desiccant so that a separate humidity control system is not required. However, the CO₂ absorption capacity of the bed is critically dependent on the bed's moisture content so that precise control of the bed water content is required for efficient utilization. Operation in the vacuum desorbed mode has not been demonstrated and it is anticipated that bed water management for this type of operation may be very difficult. The cyclic operation also requires relatively complex hardware with associated reliability problems. There is no base equipment required for this system since the CO₂ sorbent is regenerated by vacuum venting during the EVA. One significant advantage of this system is that it may be possible to adapt some of the technology already developed for space station systems and thereby reduce the development cost of the system. Therefore, this concept was retained for consideration at the total, integrated system level.

The literature survey previously cited provided evidence of some preliminary investigations into the use of other alkaline-earth hydroxides, besides LiOH, as a CO₂ sorbent. All of these materials are very basic and the reaction with the acid gas, CO₂, is basically an acid-base neutralization reaction, with the resulting formation of a carbonate salt and water. These hydroxides all have fairly high CO₂ capacity so that the bed

size is comparatively small. LiOH is preferred when the application requires an expendable sorbent because of its low molecular weight. However, as previously stated, the chemical properties of the lithium-carbonate formed during the EVA reaction are such that excessive energy is required to regenerate the hydroxide.

It was found that magnesium carbonate ($MgCO_3$) is relatively unstable at moderately elevated temperature so that thermal regeneration is possible and the relatively high solubility of potassium carbonate (K_2CO_3) in water suggested the possibility of regeneration by electrolysis of a water solution.

Magnesium carbonate dissociates into magnesium oxide (MgO) and CO_2 at elevated temperatures. Thus, if magnesium hydroxide ($Mg(OH)_2$) were used in solid form as a CO_2 sorbent during the EVA, in the same manner that LiOH is presently used, it should be possible to regenerate the resulting carbonate by simply heating the EVA canisters. The CO_2 will be driven off leaving solid magnesium oxide, which can then be hydrated to $Mg(OH)_2$ by circulating wet steam through the bed.

A workable system concept is shown in Figure 5.

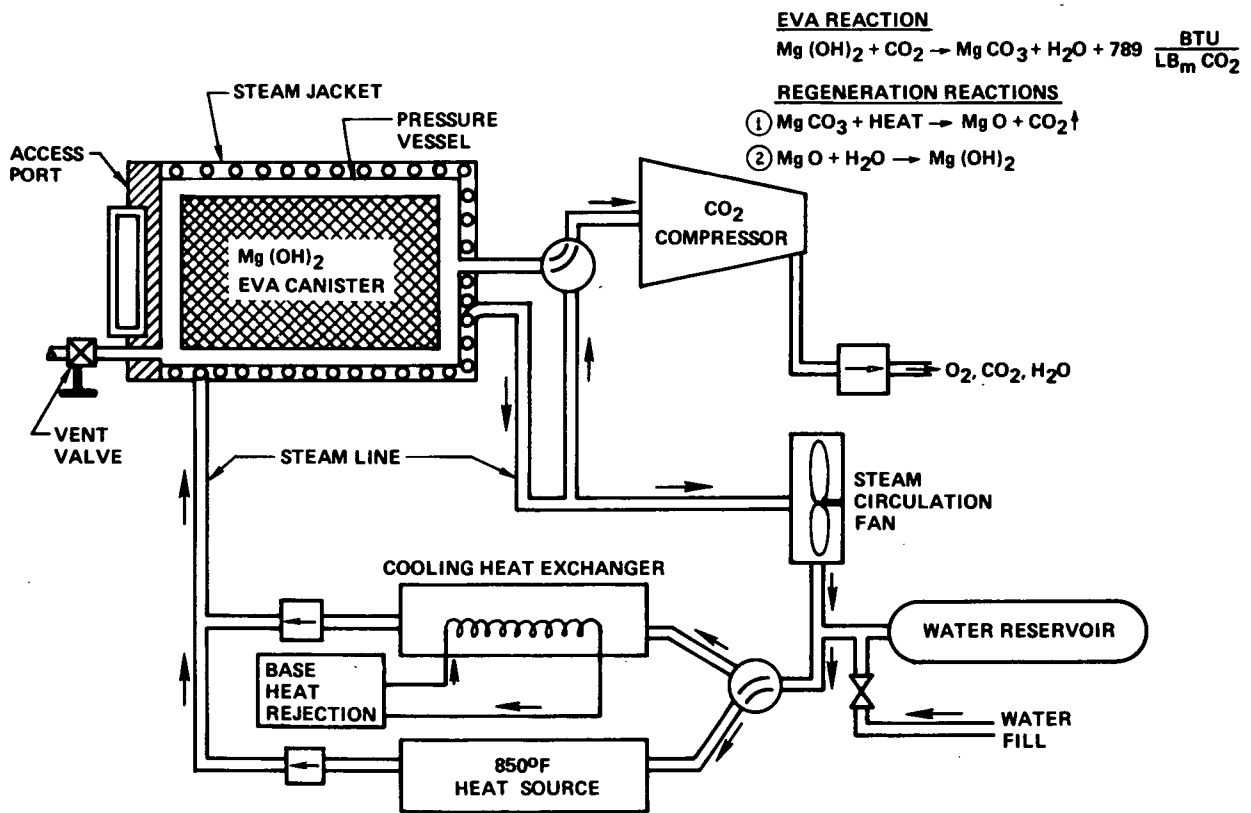


FIGURE 5 MAGNESIUM HYDROXIDE REGENERATION FACILITY

The $Mg(OH)_2$ EVA canister is placed in a heated pressure vessel at the conclusion of the EVA. The system shown uses steam to heat the canister to the required dissociation temperature; however, any heat source could be used. A compressor is used to remove the evolved CO_2 for processing by the base CO_2 reduction system. After all the CO_2 has been driven off, wet steam is introduced into the chamber to hydrate the MgO . The canister can then be removed and reused.

A similar concept has been demonstrated to be feasible (Reference [45]). However, the lifetime of $Mg(OH)_2$ pellets after repeated cycling has not been investigated. The pellets may "cake" or disintegrate to powder in a short time. Data are needed to determine whether the pellets need to be reformed after each regeneration cycle and to define the conversion efficiency of the $Mg(OH)_2$ that can be regenerated within a practical amount of time. The actual hardware weight required for regeneration of $Mg(OH)_2$ is projected to be about 230 lb_m for a two-man system. The total base penalty calculated for the system is 900 lb_m per two men with the additional weight attributed to energy penalties. Thus, the base weight of the system is critically dependent on the penalties assumed in Table III. These penalties are thought to be somewhat conservative so that the total base weight calculated for the $Mg(OH)_2$ system is probably also conservative.

The EVA operation of this CO_2 sorber system is identical to the LiOH system except that a larger canister is required. This system has considerable promise since the required technology has already been partially demonstrated.

A theoretical analysis of the energy requirements suggested the feasibility of using potassium hydroxide (KOH) as a regenerable CO_2 sorbent. Figure 6 shows a design, conceived by VMSC, that uses a circulating liquid solution of KOH rather than a solid particle bed.

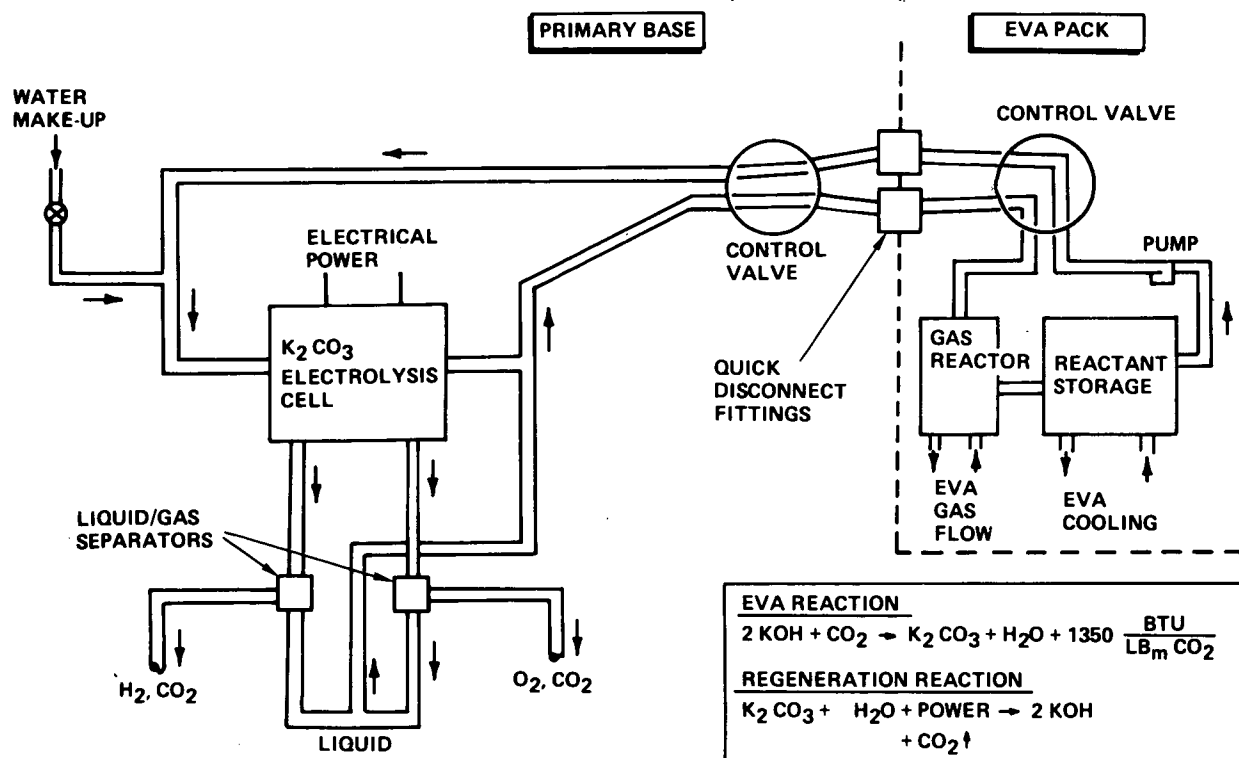


FIGURE 6 LIQUID KOH CO_2 SORBENT REGENERATION FACILITY

The advantage of this concept is that it overcomes one of the fundamental limitations to efficient utilization of a solid sorbent bed. The primary limitation is the low solid diffusion rate of reacted carbonate and unreacted hydroxide in the pellet interior. The pellets are generally made as small as possible and somewhat porous in order to maximize the surface area exposed to the gas stream. These pellets have a tendency to cake during the course of the EVA due to trapping of the product water. This increases the pressure drop and also adds to the complication of regeneration since the pellets must be reformed.

The liquid loop systems eliminate these problems since the reacted carbonate is continuously removed from the reaction site by the flowing solvent water. The EVA is started with the liquid loop filled with a strong solution of KOH in water. The gas, containing CO_2 , flows through the gas reactor where it is exposed to the liquid KOH. Part of the KOH is reacted to form potassium carbonate (K_2CO_3), which remains in liquid solution, and is then pumped to the reactant storage container. There the solution is cooled, decreasing the solubility of the K_2CO_3 , so that part of the carbonate is precipitated and filtered out of the solution. The remaining solution is then pumped back to the gas reactor. During the EVA the solution strength of the KOH is reduced as K^+ ions are removed as K_2CO_3 is precipitated out. The concentration of K_2CO_3 in the solution is determined by the solution temperature at the outlet of the reactant storage container and by the efficiency of the filtration process.

Calculations have shown this process to be theoretically feasible and the required EVA weight, volume, and power may be significantly smaller than any other regenerable system. However, considerable development remains to be done to provide an efficient and reliable EVA system.

Base regeneration, which is also shown in Figure 6, is accomplished by re-dissolving the precipitated carbonate and electrolyzing the resulting solution. The CO_2 is removed in the electrolysis cell and the result is a concentrated solution of KOH, which is ready for EVA use.

VMSC has demonstrated the feasibility of this system by means of a simple experiment. It was found, that with the simple apparatus used, it was not possible to evolve CO_2 at a significant rate without also electrolyzing water, even though it is theoretically possible to reduce the carbonate to CO_2 at a lower voltage than is required for water electrolysis. This is not a severe penalty since most base life support systems include a water electrolysis unit for the production of oxygen (Reference [26]). Therefore, a partial credit can be taken for the oxygen produced by this method. However, it is believed that it may be possible to conduct the regeneration at a lower voltage, without electrolyzing water, by employing a more sophisticated electrolysis cell than was used in the preliminary experiment.

The projected total system size for the KOH system, including all penalties, is comparable to the $\text{Mg}(\text{OH})_2$ system previously discussed. Therefore,

in order to simplify the discussion at the total system level, these systems were considered to have the same weight and volume. The potential EVA system size advantage of the KOH system over other regenerable concepts is sufficient to warrant its further investigation.

Figure 7 shows the total launch weight and volume as a function of EVA time for the most promising CO₂ control subsystems. The curves show that expendable LiOH is the smallest subsystem for less than about 50 EVA hours. Between 50 and 900 EVA hours the solid amine subsystem has the lowest total system weight; but as shown in Figure 7, the solid amine system has the largest EVA weight of all the systems considered in detail. Regenerable Mg(OH)₂ or KOH systems are the lightest total systems for more than 900 EVA hours, but as Figure 7 shows, they accomplish this by increasing the EVA weight over expendable LiOH. However, this sacrifice is believed to be worthwhile since the Mg(OH)₂ system saves more than 1000 lb_m over LiOH at 1600 EVA hours. The data presented in these figures was used to prepare similar curves for total AEPS systems.

4.3 Trace Contaminant Control Subsystem

4.3.1 The Trace Contaminant Problem

In any inhabited small, closed volume there is a potential problem with odors and toxic gases, and possibly with biological contaminants. The AEPS trace contaminant control system must be designed to eliminate any odors, toxic gases, or biological contaminants which may be generated within the AEPS atmosphere. Considerable investigation has been conducted in this area (Reference [48] - [50]), and a significant amount of space flight experience has been gained with the Mercury, Gemini, and Apollo spacecraft, and with the Apollo Extravehicular Mobility Unit (EMU). Most of the work done in this field has been directed toward contamination control for long-term occupancy of spacecraft cabins. The AEPS contaminant control problem is similar to the EMU, which is simpler than for the primary base, because of a relatively high leakage rate compared to the suit volume, and a relatively short exposure time. However, the AEPS will be used repeatedly on long duration missions.

There are four primary sources of trace contaminants in a closed life support system.

- (1) Gases from volatile materials
- (2) Electrical equipment
- (3) Chemical processes
- (4) Astronaut biological processes

It is assumed that the first two sources will not require an active control system for AEPS. Careful selection of materials can be used to minimize the introduction of odors and toxic vapors into the AEPS environment from these sources, and active electrical equipment can be shielded from the pressurized AEPS volume so as to minimize the introduction of ozone and lubricant vapors.

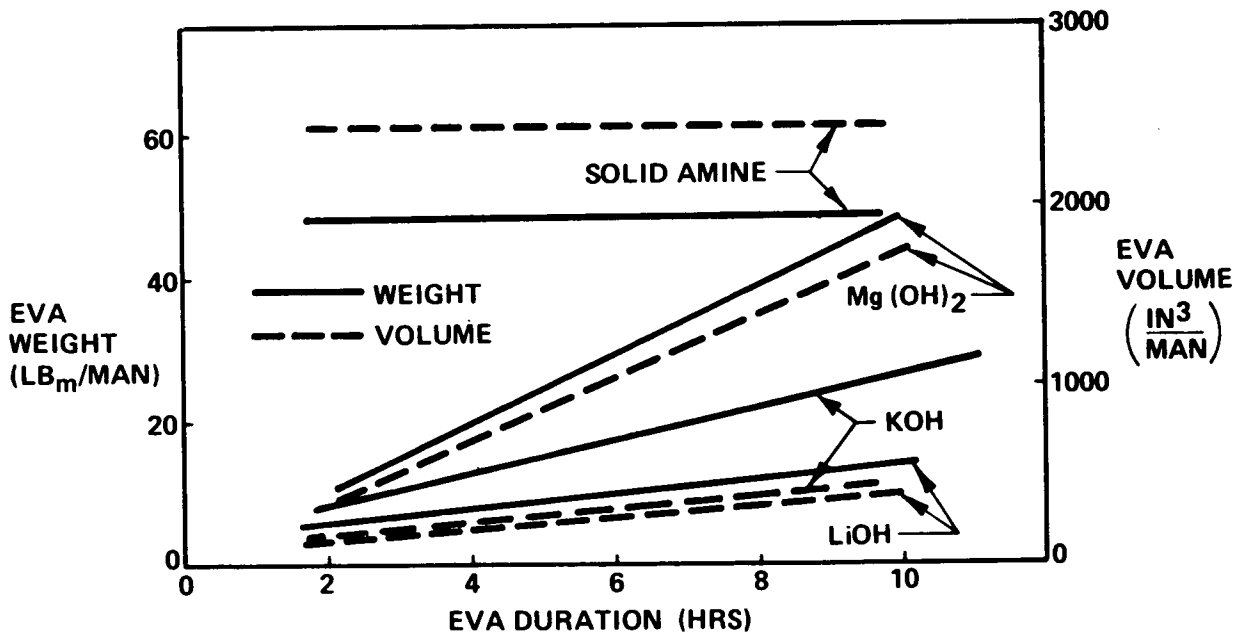
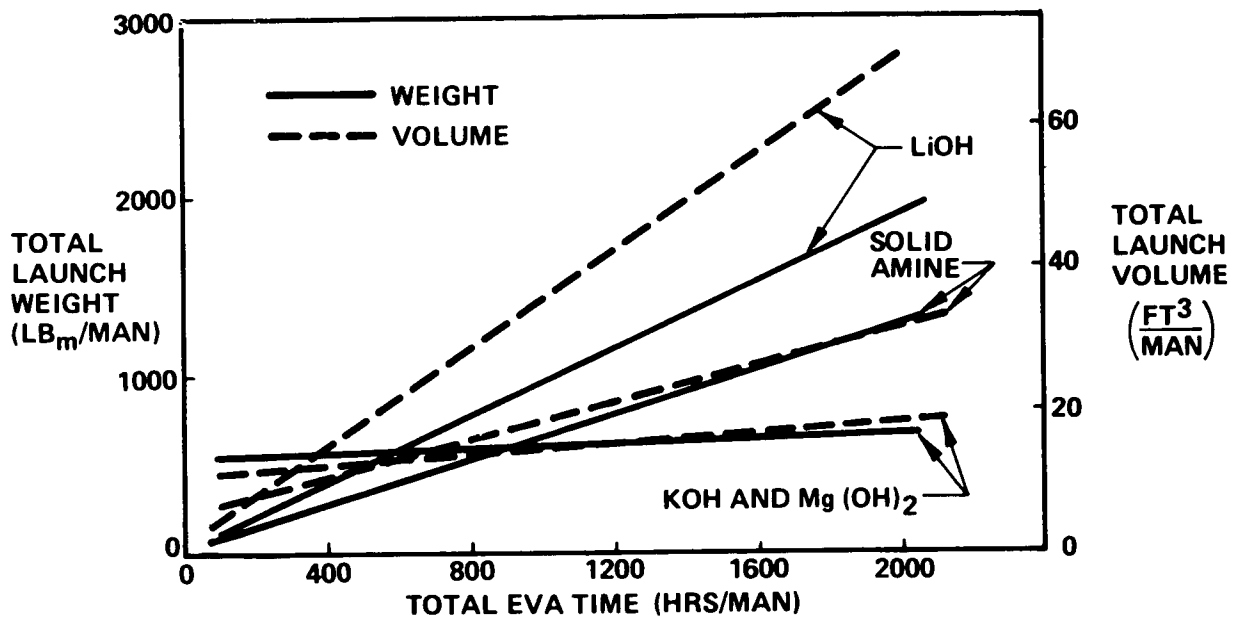


FIGURE 7 AEPS CO₂ CONTROL SYSTEM SIZE COMPARISON

Chemical reactions or processes which may be used to accomplish AEPS functions may also introduce contaminants into the system. For example, chlorate and perchlorate candles which may be used to supply oxygen contain catalysts, fuel which is required to sustain continuous decomposition, and binder materials such as fiberglass. In the relatively simple lithium hydroxide carbon dioxide control system, it is necessary to filter small LiOH particles out of the vent gas and a failure in the gas reactor required for the KOH system (Section 4.2.3) could introduce KOH liquid or vapor into the gas stream. It is assumed that the special requirements for trace contaminant control imposed by the life support subsystems will be considered in development of those subsystems.

The crewman is the source of a wide variety of noxious and toxic gases; and in addition may be host to a wide variety of micro-organisms. Although these gases are produced by, and the micro-organisms are present in most healthy individuals, they pose a potential hazard in an AEPS. The noxious and toxic gases are treated in this work. The micro-organisms and other bacteriological growths, which may be sustained in the AEPS equipment, particularly in filters and wicks, are not considered in detail. In particular, no attention is given to the possibility of mutation of non-virulent and slightly virulent forms of micro-organisms into species which are much more virulent. In this work it is assumed that a replaceable biological filter will be used in the vent gas stream, and that is the only consideration given to micro-organisms. Biological growths in equipment must be considered on the total AEPS system level.

A last problem which may be encountered involves cleaning equipment used on planetary surfaces. Dust is known to pose a serious problem on the lunar surface, based on flight experience, and it is difficult to remove from garments and equipment. The full extent and implications of these problems on system design are not known at present; and this was not considered in detail in this study.

The emphasis in this study was placed on the control of trace contaminants generated by the crewman himself, while it is realized that other sources may be present.

4.3.2 Biological Contaminants

Major substances given off by normal human biological processes are presented in Table IX. The most significant of these substances are shown in Table X along with the generation rate (Reference [48]), the allowable concentration in the AEPS atmosphere, and the probable toxic effect of the contaminant on the human body.

<u>SUBSTANCE</u>	<u>PROBABLE SOURCE</u>
ACETONE	URINE, EXPIRED AIR
ALLYL ALCOHOL	DECOMPOSITION OF BODY WASTES
AMMONIA	FECES, FLATUS, SWEAT
CARBON MONOXIDE	EXPIRED AIR
BUTYRIC ACID	FLATUS
CARBON DISULFIDE	FECES, FLATUS
HYDROGEN	FECES, FLATUS
HYDROGEN SULFIDE	FECES, FLATUS
ISOPRENE	EXPIRED AIR
METHANE	FECES, FLATUS
METHYL ALCOHOL	EXPIRED AIR
PROPIONIC ACID	FECES, FLATUS
SULFUR DIOXIDE	URINE

TABLE IX TYPICAL BIOLOGICAL CONTAMINANTS

<u>CONTAMINANT</u>	<u>GENERATION RATE (LB/HR)</u>	<u>ALLOWABLE CONC. (P. P. M.)</u>	<u>TOXIC EFFECT</u>
AMMONIA	4.15×10^{-5}	10	IRRITANT
CARBON MONOXIDE	1.15×10^{-6}	20	BLOOD POISON
HYDROGEN	8.20×10^{-6}	41,000	ASPHYXIAN
HYDROGEN SULFIDE	1.79×10^{-8}	2	IRRITANT
METHANE	7.20×10^{-4}	200 – 50,000	ASPHYXIAN
METHANOL	4.15×10^{-6}	40	NARCOTIC-IRRITANT
SULFUR DIOXIDE	4.15×10^{-7}	1	IRRITANT

TABLE X AEPS TRACE CONTAMINANT MODEL ATMOSPHERE

4.3.3 Threshold Limit Values

There are little data available in the literature on the cumulative effects of long-term exposure to the contaminants found in a closed spacecraft atmosphere. Data compiled for 90-day exposure in nuclear submarines is probably the most directly applicable to space life support systems. However, these data are for a total pressure of 760 mm Hg and thus must be modified for the lower atmospheric pressure in an AEPS.

The American Conference of Governmental Industrial Hygienists has established threshold limit values (TLV) for a wide range of contaminant substances. The TLV values are considered to be safe concentration levels for repeated, continuous 8-hour exposure, 5 days per week. Since the pertinent data for space applications are lacking, an arbitrary limit of 0.1 times the TLV concentration is commonly used in the design of trace contaminant control systems. If an astronaut spent 16 hours per day in a base with 10% TLV contaminant concentration and 8 hours performing an EVA with 100% TLV, his average contaminant concentration exposure for 24 hours would be 40% TLV. In addition, the generation rates may not be constant and may have peaks much higher than the average generation rate. Thus the conservative 10% TLV concentration was used for the AEPS study.

Evaluation of the methane maximum allowable concentration in AEPS indicates that use of 0.1 TLV may be overly restrictive. The primary dangers associated with methane are asphyxiation and the explosive hazard and allowable concentrations up to 50,000 ppm have been found in the literature (Reference [44]). For this reason it may be unrealistic to set the maximum allowable concentration at 0.1 TLV and an allowable concentration of 50,000 ppm was assumed for methane.

Other factors must also be considered. The TLV concentrations are often considerably above the odor threshold for many substances. The odor threshold concentration rather than the toxic TLV concentration will be used for such substances.

A further consideration is the synergistic effect which might result from the presence of more than one contaminant. The physiological effects of different contaminants may be similar so that the cumulative concentration of a group of contaminants may be harmful, even though the concentration of each contaminant is below the TLV values.

The concentration values shown in Table X are in good agreement with most sources (References [48], [49]), and these were used for the AEPS contaminant control system design.

4.3.4 Trace Contaminant Control Techniques

Contaminant control systems for space flight use have been extensively investigated and, for large closed volumes, a system employing a biological filter, charcoal adsorbent cartridge and a catalytic burner

will maintain all contaminant levels below the recommended maximums. The following possible systems were considered for the AEPS application:

- (1) No active control-leakage only
- (2) Periodic suit purge
- (3) Biological filter, activated charcoal
- (4) Filter, charcoal, and catalytic burner
- (5) Chemical control systems

These systems are listed in order of increasing complexity and size.

4.3.5 AEPS Leakage

The composition of a gas mixture in a closed volume will change with time if the container leaks. This occurs because the diffusion rates for gases of low molecular weight are greater than for gases with large molecules. Therefore, light gases such as methane will leak at a faster rate than a heavier gas such as oxygen. This preferential leakage may be sufficient to keep contaminant gases with low production rates below their allowed concentration.

The leakage rate specified for AEPS is 180 sccm which is equivalent to 0.0381 lb_m/hr. This is the same leakage rate specified for the Apollo A7L suit.

The concentration of a contaminant if the leakage and generation rates are known is:

$$C = C^* (1 - e^{-K\tau}) + C_i e^{-K\tau} \text{ (ppm)}$$

where

$$C^* = \frac{M}{M_C} \left[\frac{\dot{M}_C}{\dot{M}_L + N_C \dot{M}_R} \right]$$

$$K = \frac{RT}{MPV} \left[\dot{M}_L + N_C \dot{M}_R \right]$$

- C = transient concentration
- C* = steady state concentration
- C_i = initial concentration
- τ = time
- M = molecular weight of cabin gas
- M_C = molecular weight of contaminant
- \dot{M}_C = contaminant production rate (values from Reference [18])
- \dot{M}_L = leak rate
- \dot{M}_R = flow rate through the system
- N_C = efficiency of contaminant removal

R = universal gas constant
T = gas temperature
P = gas pressure
V = gas volume

(Reference [49])

The nominal PLSS flow rate of 7 lb_m/hr with a 3.5 psia O₂, 4.0 psia N₂ atmosphere was used to determine trace contaminant removal requirements. Since there is very little difference between the molecular weights of O₂ and N₂ these results are also valid for other gas mixtures.

The above equation was used to calculate the concentrations of the main biological contaminants at the end of 8 hours for different values of removal efficiency. The results are plotted in Figure 8 along with the maximum allowed concentrations. These results indicate that methane and ammonia are the only contaminants that may require active control. The other contaminants have sufficiently low generation rates relative to allowable concentrations so that suit leakage only, with about 5% removal efficiency is adequate to keep the concentrations within allowable limits.

This result is somewhat misleading since the calculation was made assuming a constant generation rate over the entire EVA. Thus, while substances such as H₂S require little control if only the total mission is considered, the short term odor effect requires control consideration. Therefore, suit leakage alone is not sufficient to provide complete control for an AEPS system.

The AEPS space suit could be periodically purged to effectively increase the leakage rate, and thus provide control for methane and ammonia. However, the required quantity of make-up atmosphere is excessive and safety considerations associated with venting the suit make the purge approach undesirable.

4.3.6 Biological Filter with Activated Charcoal

Activated charcoal is widely used for odor removal, and this is very desirable in AEPS. However, charcoal will not effectively adsorb low molecular weight gases such as methane and ammonia. The addition of phosphoric acid (H₂PO₃) to charcoal increases the ammonia adsorption capacity, and the addition of potassium hydroxide (KOH) increases the capacity for acid contaminants. Thus, this system is adequate for all contaminants.

The biological filter and the charcoal can be regenerated, however, the expendable weight is only about 0.1 lb_m per man EVA so that regeneration will not be profitable for AEPS unless a great many sorties are undertaken on a mission.

4.3.7 Recommended Subsystem Concept

A trace contaminant control cartridge containing activated charcoal and biological filters was selected for the AEPS system. The

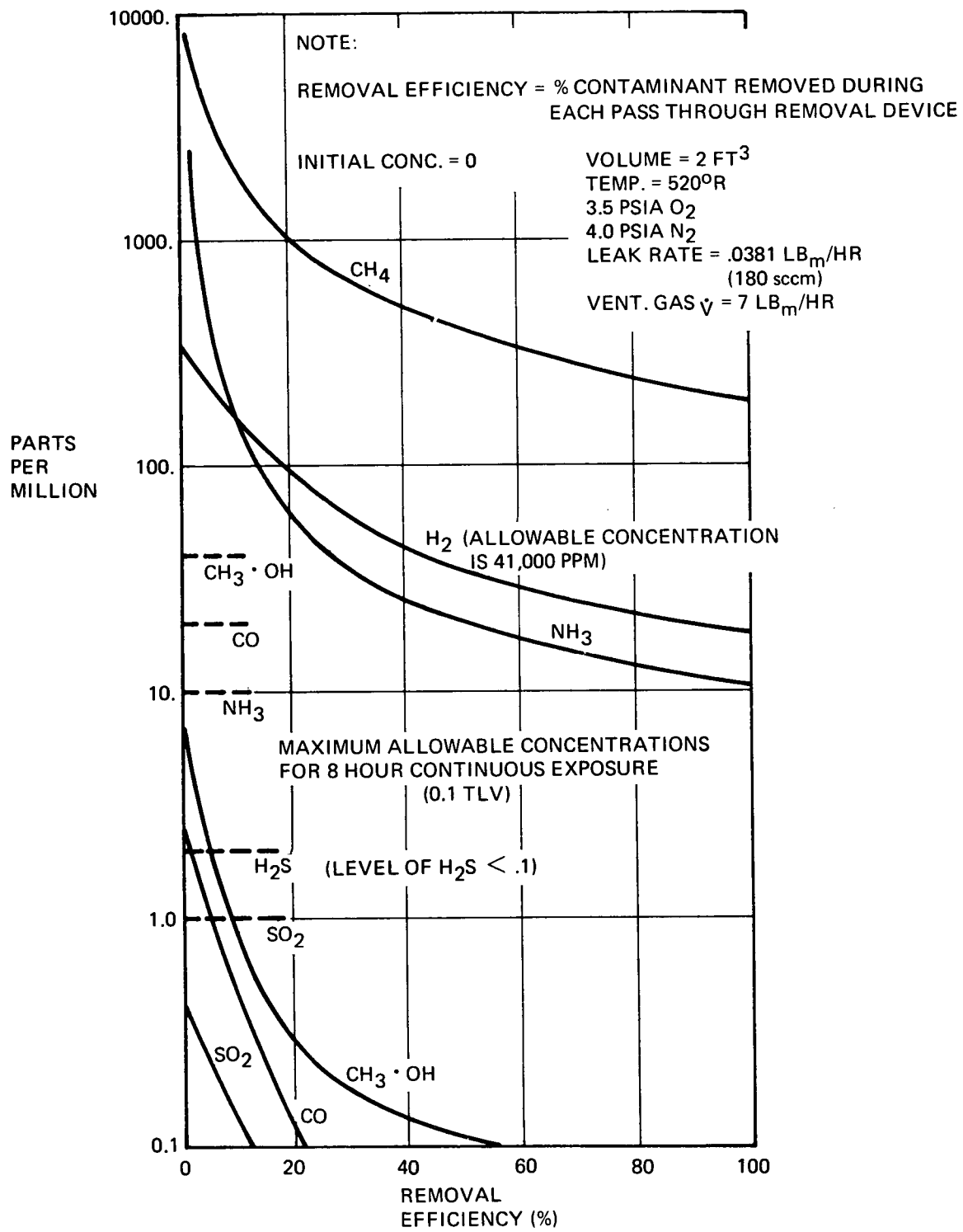


FIGURE 8 TRACE CONTAMINANT CONCENTRATION AFTER 8 HOURS AS A FUNCTION OF REMOVAL EFFICIENCY

charcoal bed is divided in half with 50% of the charcoal impregnated with a solution of KOH and the remainder with phosphoric acid. The addition of these chemicals improves the adsorption efficiency of acidic and basic contaminants. The cartridge should be located upstream of the humidity control system, since the presence of moisture further improves the adsorption efficiency of the chemically impregnated beds.

4.4 Thermal Control Subsystem

The purpose of the AEPS thermal control subsystem is to maintain the crewman at a comfortable temperature level under all conditions. In addition, other AEPS systems, notably the CO₂ and humidity control systems, may require cooling. The system heat loads were discussed in Sections 3.5 and 3.6.

Gemini experience has shown that gaseous convective cooling of a suited crewman is inadequate when the crewman is working at the high metabolic rates expected during orbital or surface EVA operations. Therefore, the AEPS study baselined a circulating water cooling system similar to the Apollo LCG. The Apollo EVA thermal control system has a network of flexible tubes that are held in close contact with the astronaut's skin. Chilled water is circulated through the tubes and heat is removed from the astronaut by conduction from the skin into the tubes. The water is then circulated through a sublimator in the backpack. The low heat exchanger effectiveness of the current LCG requires an inlet temperature of about 40°F in order to remove the maximum metabolic load. This low temperature in close contact with the skin can create physiological and comfort problems for the crewman. A brief investigation showed the feasibility of producing a more effective heat transfer between the heat sink and the LCG that could operate with inlet temperatures in the range of 60 to 70°F at the maximum metabolic load. This higher temperature level is beneficial to some heat rejection concepts so that an advanced LCG was assumed to be available for the AEPS thermal control subsystem.

A PLSS-type heat rejection system will expend water at an average rate of 1-2 lb_m per EVA manhour. The water required for heat rejection represents about 3/4 of the total PLSS expendable requirement. Therefore, a fully or partially closed heat rejection system offers a tremendous opportunity to reduce the total launch weight required to support multiple EVA operations. Fully closed systems may be rate limited, so that a system designed to handle the peak load would be unnecessarily clumsy. Since the peak load is expected to occur at infrequent intervals and for relatively short periods, it might be advantageous to combine a closed system for the baseline heat load with an expendable "top off" system to handle transient peak loads.

The AEPS heat rejection systems must be designed to operate without crewman discomfort at the minimum heat load, to have the capacity to reject the nominal heat load as an average over an 8-hour sortie, and to have heat rejection rate capacity sufficient to accommodate the maximum heat load. The average heat load of 1200 BTU/hr is that which the system must be capable of rejecting over all sorties on a mission.

4.4.1 AEPS Heat Loads

The design heat loads for the AEPS were discussed in Section 3.6, and the technique used in this study for calculating the heat load was described. The heat load is a function of the local thermal environment and varies considerably from one mission to another. Table XI gives the minimum, average, nominal and maximum expected total heat loads for the design missions.

MISSION	MINIMUM (MR=500 BTU/HR)	AVERAGE (MR=1200 BTU/HR)	NOMINAL (MR=1600 BTU/HR)	MAXIMUM (MR=3500 BTU/HR)
EARTH ORBIT	525	1330	1800	3950
LUNAR SURFACE	350	1460	1925	4400
MARS SURFACE	350	1160	1650	3825

TABLE XI AEPS DESIGN HEAT LOADS

4.4.2 Definition of Rate Limited and Capacity Limited Systems

Table XI indicates that while there are significant differences in the heat load on different missions, the variance in heat load on a given sortie may be much greater. The wide variance in heat loads on a given sortie has a significant impact on the selection of the heat rejection system. The systems which might be used for AEPS heat rejection fall into one of two categories; either they are heat transfer rate limited or they are total capacity limited. These characteristics of systems are diametrically opposite, and systems tend to be dominated by one characteristic or the other. For example, a water evaporation system can easily be designed to operate at any heat load from the minimum to the maximum: the system is limited by the large quantities of water which must be carried to enable the system to reject the total heat load over a sortie. So the evaporation system is said to be capacity limited. A radiator system, on the other hand, grows in size approximately in a linear fashion with the maximum heat load which must be rejected; but it is only slightly influenced by the integrated total heat load which must be rejected over a sortie. Thus the radiator system is said to be rate limited.

4.4.3 Top-Off Systems

The expected short transient duration of the peak heat load makes the use of a "top-off" system a potentially attractive concept for AEPS. This would involve the use of a regenerable system to reject some fixed portion of the heat load (probably the nominal or the average) with

a separate expendable system to reject any excess heat load when it occurs. This approach may produce the optimum size and weight heat rejection system, and it has some other advantages, namely,

(1) The "top-off" system may also serve as a back-up or emergency system, and

(2) A rate limited heat rejection system which is designed to reject the maximum AEPS heat load may have control problems when rapid transients from the lower heat loads are encountered.

4.4.4 Candidate Heat Transport Processes

Heat transport processes which were considered for AEPS thermal control are shown in Table XII.

MECHANISM	MASS & HEAT TRANSFER			PHASE CHANGE			WORK	CHEMICAL REACTION
	CONDUCTION	CONVECTION	RADIATION	EVAPORATION	FUSION	CRYSTALLINE STRUCTURE CHANGE		
GOVERNING EQUATION	$q_L = \frac{KA}{X}(T_L - T_S)$	$q_L = hA(T_L - T_S)$	$q_L = \sigma \epsilon A(T_L^4 - T_S^4)$	$q_L = \dot{m}\lambda$	$q_L = m\lambda$	$q_L = m\lambda$	$q_L = w \left(\frac{T_L}{T_S - T_L} \right)$	$q_L = m\Delta h_D$
LIMITING FACTOR	RATE	RATE	RATE	CAPACITY	CAPACITY	CAPACITY	RATE	CAPACITY
TYPICAL CANDIDATE SYSTEMS	SUB-SURFACE HEAT SINK	MARS HEAT EXCHANGER	SPACE RADIATOR	SUBLIMATOR	ASTRONAUT HEAT SINK (AHS)	AHS	VAPOR COMPRESSION REFRIGERATOR	AHS
EXPENDABLE REQUIREMENTS	—	—	SMALL	LARGE	NONE	NONE	SMALL	NONE

NOTE: T_S = SINK TEMPERATURE
 T_L = SYSTEM HEAT REJECTION TEMPERATURE

SYSTEMS SELECTED FOR FINAL SYSTEM INTEGRATION

- SPACE RADIATOR
- SUBLIMATOR
- AHS (WATER SELECTED AS FUSIBLE MATERIAL)
- REFRIGERATOR

AHS SYSTEM USES REPLACEABLE MODULES TO REDUCE PACK WEIGHT

REFRIGERATION SYSTEM USES PART-TIME (70%) UMBILICAL WITH AHS "TOP-OFF"

TABLE XII MEANS FOR ACCOMPLISHING HEAT REMOVAL FROM AEPS

In general the desired system characteristics of low expendable requirements and minimum maneuvering constraints (low system volume and weight) are diametrically opposed.

Conduction heat transfer into the planetary surface is impractical because of the AEPS mobility requirement. The storage of heat in the planetary surface could be used in the appropriate cases, but a considerable amount of site preparation is required to make this approach operable, and maneuverability would be restricted.

Convection heat transfer is one of the prime mechanisms used for cooling the crewman, by airflow and by coolant flow in the LCG; however convection is limited as the ultimate heat removal technique in a space application because of the lack of an adequate heat sink. In the Mars application there is sufficient atmosphere (the pressure is about 0.088 psia, 90% CO₂) so that convection is a factor which must be considered; however, it is not adequate to be the primary heat sink at high metabolic rates. A blow-down type of oxygen supply system could marginally provide cooling to the crewman by convection (and the attendant mass transfer associated with sweat evaporation from the crewman's skin); however, this would probably be best applied as a relatively short duration back-up system because of the large expendable atmosphere requirement.

Radiation offers considerable promise as the heat transfer mechanism from an AEPS because it is not dependent on any medium being in contact with the AEPS. There is, of course, a requirement that a line-of-sight relationship with a low-temperature heat sink be maintained. Removal of the maximum allowable heat rate generated by an AEPS system by radiation, without the use of extended area is not physically possible (based on a crewman area of 20 ft² and a skin temperature of 80°F). The radiation heat removal rate is reduced in actual practice because of radiation between external suit and equipment surfaces and because the space suit must be insulated to accommodate cold conditions (when the crewman has a low metabolic rate) and extreme hot conditions (when the crewman is in the vicinity of hot objects such as the lunar surface). This means that, while the space suit surface can be used to reject a portion of the heat load, it cannot reject the maximum heat load, so an alternate means of heat rejection is required. This could be extended radiation area, probably in the form of a space radiator, or some other suitable heat rejection device. A deployed radiator obviously creates a maneuverability constraint, and there may be difficulty in maintaining proper radiator orientation in some instances.

Degradation of radiator surface properties due to ultra-violet radiation and high energy particle impingement may pose a significant problem, particularly on the lunar surface where the use of a radiator may be marginal in many locales. Contamination of radiator surfaces by dust may also pose a significant problem on planetary surfaces. Despite these problems, radiation is a promising means for providing the ultimate heat sink for an AEPS.

Refrigeration systems are widely used in terrestrial applications. The function of these systems is to raise the temperature at which the ultimate heat rejection is accomplished. In terrestrial applications, the ultimate heat rejection is usually to the atmosphere via a convection process, with evaporation processes (cooling towers) also being in wide use. For a space application, the ultimate heat rejection would probably be accomplished by radiation. Work-driven systems may be divided into two classifications; vapor cycles and gas cycles. Vapor cycle refrigeration systems are the most widely used in terrestrial applications; both shaft-work driven and heat-driven systems enjoy commercial success. Gas cycles

are used in turbine-powered aircraft in an open-cycle fashion with the air being supplied in the form of bleed-air from the jet-engine compressor. Heat driven refrigeration systems, including systems where the refrigerant is absorbed in a chemical bed which is regenerated at the base, were considered and found to require much larger weight and volume than mechanically driven systems. The vapor compression cycle is the most probable candidate of refrigeration system for an AEPS application because the system is lighter and more compact than other refrigeration systems, and the driving energy can be conveniently supplied by a moderately sized battery. Refrigeration is potentially attractive for an AEPS because

(1) The radiation sink temperature for much of the lunar surface is above the desired AEPS metabolic heat sink temperature, and

(2) There is generally an advantage in reducing the required radiator area (which can be accomplished by raising the radiator temperature).

Phase change offers considerable promise for the AEPS heat rejection system. Evaporation has been used extensively as a heat sink in space applications; it provides a small, light weight system for relatively short duration EVA sorties. The expendables required over a long mission involving many sorties become prohibitively large, however. Evaporation is very attractive as a top-off system because of the light weight. Fusible materials have also been used extensively in space applications, usually to dampen or smooth out temperature excursions where the external environment is cyclic, or where operation (and thus internal heat generation) is intermittent. In the AEPS application the 8-hour sortie duration is long enough to reduce the potential of fusible material. However, the identification of a fusible material with superior thermal properties, or the potential for marriage of the fusible approach to some other heat rejection technique make the fusible heat sink a strong candidate. Crystalline structure change materials are very similar to fusible heat sink materials, except that the phase change involved is from one solid state to another solid state with a different crystalline structure. This obviously offers a distinct advantage in container design over fusible materials which go from a solid to a liquid state. The primary problem in solid-to-solid phase change systems is the same as for fusible heat sink systems; namely, finding a material with a very high heat of transition and a suitable transition temperature (of approximately 0°F to 50°F). No suitable solid-to-solid phase change materials were found.

Endothermic chemical reactions which absorb heat could be used to accommodate AEPS heat rejection. This would be particularly valuable if it could be combined with a chemical reaction already required by the AEPS system such as CO₂ control, humidity control, or power production. No chemical reactions were found that combined the required high heat of reaction in the required temperature range, with non-toxic reactants and products, to allow the construction of a safe, reliable system. Therefore, this approach was not considered further.

4.4.5 Selection of Heat Rejection Subsystem

The primary criteria used for selecting the AEPS heat rejection subsystems were minimum EVA size, mobility restriction, and expendables, combined with reliability and safety for the astronaut in case of failure. As discussed earlier, it was found that the objectives of minimizing EVA size and expendables were contradictory, so that a relatively large EVA system is required for a closed heat rejection system. The most promising candidates are shown in Table XIII.

CONCEPT	SELECTED SYSTEM
1. EXPENDABLE HEAT SINK	SUBLIMATOR, FLASH EVAPORATOR
2. FUSIBLE HEAT SINK	FUSIBLE WATER ASTRONAUT HEAT SINK (AHS)
3. REFRIGERATION MACHINE	VAPOR COMPRESSION CYCLE
4. RADIATOR	PORTABLE RADIATOR PACKAGE

TABLE XIII FINAL CANDIDATE HEAT REJECTION SUBSYSTEMS

It was found that no heat rejection system that could operate for 8 hours without expendables was small enough to be integrated entirely into a backpack system. Therefore, some type of a support system, separate from the backpack, is required. This support system could be mounted on a "MET-type" transporter or it could be installed on a powered vehicle.

There are two functionally different methods of supporting the AEPS backpack from a separate system. The two systems can either be connected by an umbilical or the support system could hold cooling modules that can be installed into the AEPS pack as required. VMSC evaluated both approaches and found that it was not possible to prove one method superior to the other based on the general AEPS guidelines. It was assumed that any umbilical system must have the capability to operate without the umbilical for 30% of the EVA duration. Therefore, the radiator and refrigerator systems, which have the capability to operate as completely closed systems, are considered to be supplemented by expendables, since expendables may be used during the non-umbilical portion of the EVA.

The expendable heat sink concept has the lowest EVA weight and volume but the highest total weight for a large number of EVA's. The sublimator system, as used in the Apollo PLSS, is a compact, reliable system that is ideally suited to missions where only a few EVA's are required. However, it is not suitable for use as an expendable, "Top-Off", system due

to its relatively poor response characteristics from start-up and waste of water during the "dry-out" phase. The flash evaporator is an expendable system being developed by VMSC, under contract to NASA-MSD, for a potential shuttle application. As applied to AEPS, it would offer no expendables advantage over the sublimator when used as the primary cooling system. However, its response to varying heat loads make it ideally suited for use as an expendable "top-off" system.

The use of a fusible material allows a completely closed heat rejection system. Water was selected as the fusible material due to its high heat of fusion and the fact that it is completely non-toxic in all forms. In addition, the solid-to-liquid phase change occurs at a temperature and pressure that minimizes hardware design problems. The use of fusible water also allows the system to incorporate a back-up evaporative mode with proper hardware design.

The heat of fusion of ice is roughly 15% of the heat of vaporization so that 6 to 7 times as much water must be transported for use in the fusible as compared to the expendable mode. Approximately 100 lb_m of ice may be required per man, to reject the specified AEPS heat load and this is too heavy to be carried conveniently in a backpack. In order to minimize mobility constraints, the ice may be modularized into smaller, more manageable portions, with fresh modules carried in an insulated container. The melted ice modules are replaced with frozen ones as required. This is required every 1-2 hours depending on the heat load and the size of the module. However, if for some reason it is not possible to change modules when required, the astronaut could switch to the evaporative mode and continue the full EVA with no restrictions except for the water expended. The ice modules are refrozen at the base between EVA's. This system concept has been designated the Astronaut Heat Sink (AHS) and it is felt to offer considerable promise in reducing the expendables required for EVA heat rejection.

The basic AHS concept is extremely simple. An aluminum pack containing 15 lb_m of ice, is mechanically clamped between two heat exchanger modules, and heat is rejected by melting the ice. A mechanical interface between the heat sink and the LCG fluid has a reliability advantage since the LCG loop is not broken during routine module replacement. The total subsystem mass is too large to be included in a backpack so the ice is divided into modules with fresh modules carried in an insulated container. A spent (melted) module is replaced with a fresh one from the storage container as required. The AHS is carried in a chest pack to facilitate AHS module replacement.

The heat capacity of each AHS can be increased by sub-cooling the ice during the regeneration mode and heating the melted water above 32°F during use. A total heat sink of 175-200 BTU/lb_m ice can be achieved with only a moderate amount of sub-cooling. Moderate sub-cooling was assumed, since cooling to very low temperatures increases the regeneration penalty and also complicates the subsystem design since freezing of the LCG water must be prevented.

The AHS has a unique contingency mode of operation which is possible because water is used as the heat sink material. At any time when it is not convenient to change AHS modules the AHS in use can be converted

to an evaporator simply by opening the manual vent valves. The 15 lbm of water can then be expended by controlled evaporation. This extends the capability of the AHS system to allow a complete 8-hour EVA without the support modules but with a penalty in water expended. This contingency mode adds considerable flexibility to the AHS concept.

A fusible AHS type heat sink is assumed to be integrated into the backpack for use as the "top-off" system required for the radiator refrigeration systems. This allows 1-2 hours of non-umbilical operation without expending any water and a further 5-6 hours is available by using the expendable mode.

The AHS packs are regenerated at the base simply by refreezing the ice. In some environments, such as the lunar night, the AHS packs can be regenerated without any special equipment by exposing them to the exterior environment. However, the total system weight calculated for the AHS system includes a base freezer system with all associated penalties.

Another approach to using the heat of fusion of ice is to connect the backpack to a large AHS by means of an umbilical. This large AHS could be conveniently mounted on a powered or a "MET-Type" transporter. It would provide all AEPS heat rejection when the umbilical could be used but a secondary system would be required in the backpack to allow operation without the umbilical. This system eliminates the requirement for changing modules during the EVA but the umbilical does restrict mobility to some extent. A heat exchanger is included in the backpack to allow a fluid loop separate from the LCG to be circulated through the umbilical.

Both of these AHS systems have a relatively large EVA weight per man but they are very compact. This minimizes the transportation difficulty, but some sort of small transporter is required.

Both the simple radiator and the refrigeration systems are rate limited and it was found that they were prohibitively large when designed to reject the maximum heat load. However, this maximum heat load is expected to occur infrequently and for short durations so that a more practical approach is to design the primary system to reject the average heat load with a secondary "top-off" system to accommodate the transient peaks. It was found that for an average metabolic load of 1600 BTU/hr the total system heat load, including equipment cooling and a nominal environmental heat leak, is about 2000 BTU/hr. Therefore, this value was taken as the baseline heat load for the design of the primary system.

A simple radiator system was found to be the lightest weight, closed heat rejection concept available. However, this system suffers several disadvantages that limit its applicability. A large radiator area is required since the radiating temperature is limited to the temperature available from the LCG and will therefore be less than about 70°F. This limits the heat rejection from the radiator to a maximum of 140 BTU/hr ft²

so that the minimum possible radiator area is about 14 ft^2 for 2000 BTU/hr. The actual area will be considerably greater due to limitations imposed by radiator fin effectiveness, surface optical properties, and the influence of the thermal environment. If a secondary radiator loop is used to avoid circulating the LCG fluid directly through the radiator, the temperature drop across the required heat exchanger will further reduce the radiating temperature. Any thermal radiation incident on the radiator surface will decrease the radiator's net heat rejection per unit area. In some daytime thermal environments, such as inside a lunar crater or near mountains, the infrared radiation from topographical features can render a simple radiator completely useless. The radiator can be shielded or positioned by an orientation system to minimize the incident radiation, but these additions increase the weight and volume of the system so that it is not competitive with several other concepts. However, a radiator would be a very attractive system for a Martian EVA since the thermal environment is much less severe than on the moon.

The problems encountered with the simple radiator can be overcome by using a refrigeration cycle to increase the radiator temperature. A vapor compression refrigeration cycle was selected due to its high coefficient of performance (COP) and compact size. The energy required to drive the system is supplied by a lithium-halide battery.

A conceptual design for an AEPS vapor compression refrigerator was created to allow weight, volume, power, and expendables estimates to be made. It was found that, using conservative estimates for motor and compressor efficiency, a COP of 2.9 could be achieved with an evaporator temperature of 40°F and a 130°F condenser temperature. The total EVA weight of the system, including power supply and radiator, was found to be about 70 lb_m for a 2000 BTU/hr system. This system employs a 25 foot umbilical with the evaporator built into the AEPS pack. Thus, any failure in the umbilical system would not cause a loss of LCG fluid, since the evaporator acts as a heat exchanger between the LCG loop and the refrigerant. A "top-off" system is also included in the backpack, bringing the total heat rejection system weight to about 95 lb_m . This system would provide cooling for non-umbilical operations, to accommodate transient peak heat loads, and in case of refrigeration system failure. The only base requirement for this system is recharge of the EVA battery.

The modular and umbilical approaches to AEPS thermal control are illustrated in Figure 9. This figure shows an AHS chest pack with the insulated storage container integrated into a small "MET-type" equipment transporter. The umbilical refrigeration system is shown mounted on a small, powered transporter. This system could also be mounted on a man-powered equipment transporter or detached from the transporter for use at a work station. Both of these approaches have considerable promise for a wide range of AEPS missions.

The weights and volumes of these promising systems are shown in Figure 10. The figure shows that the expendable weight of the sublimator

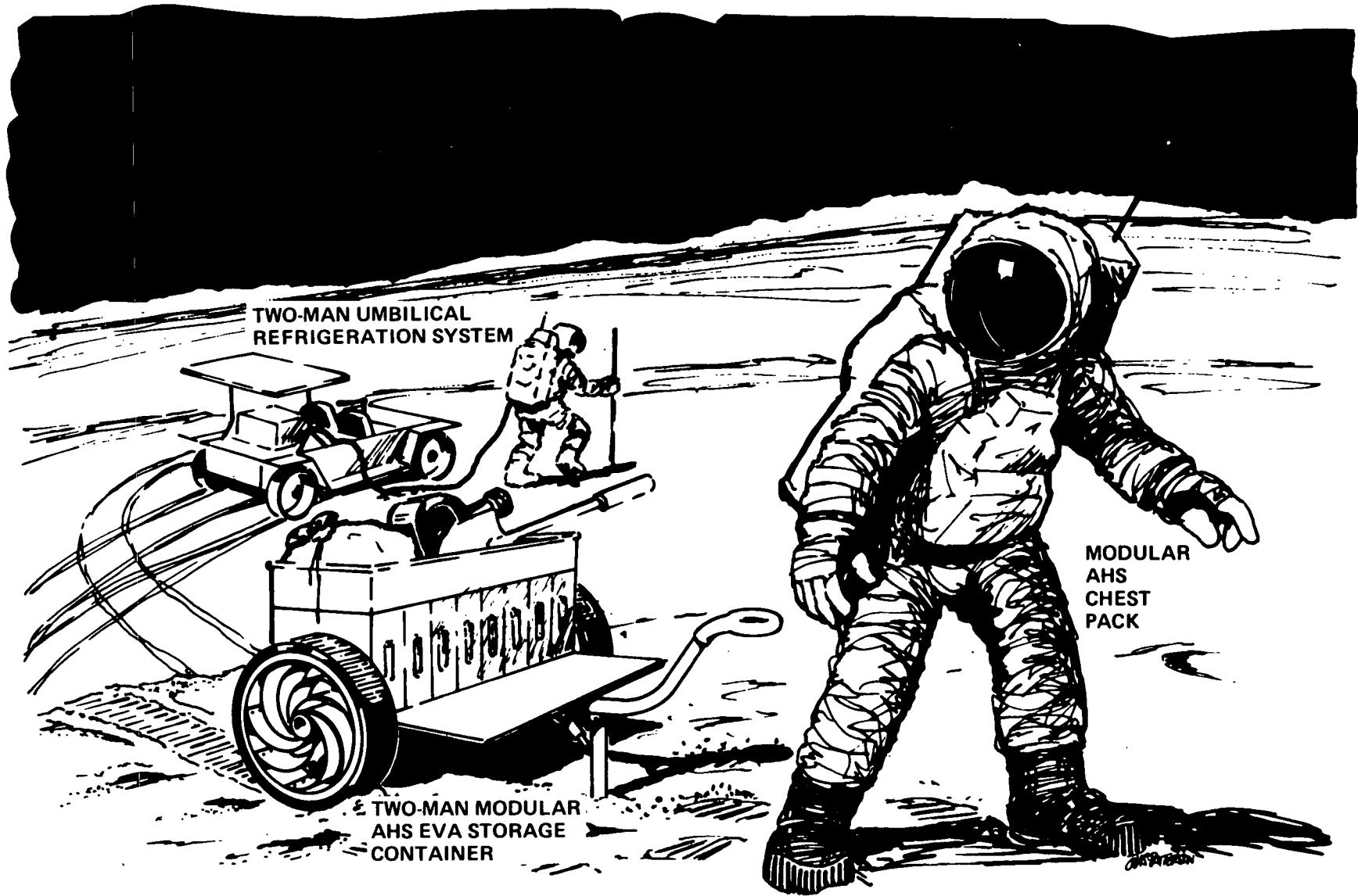


FIGURE 9 MODULAR AND UMBILICAL APPROACHES TO AEPS THERMAL CONTROL

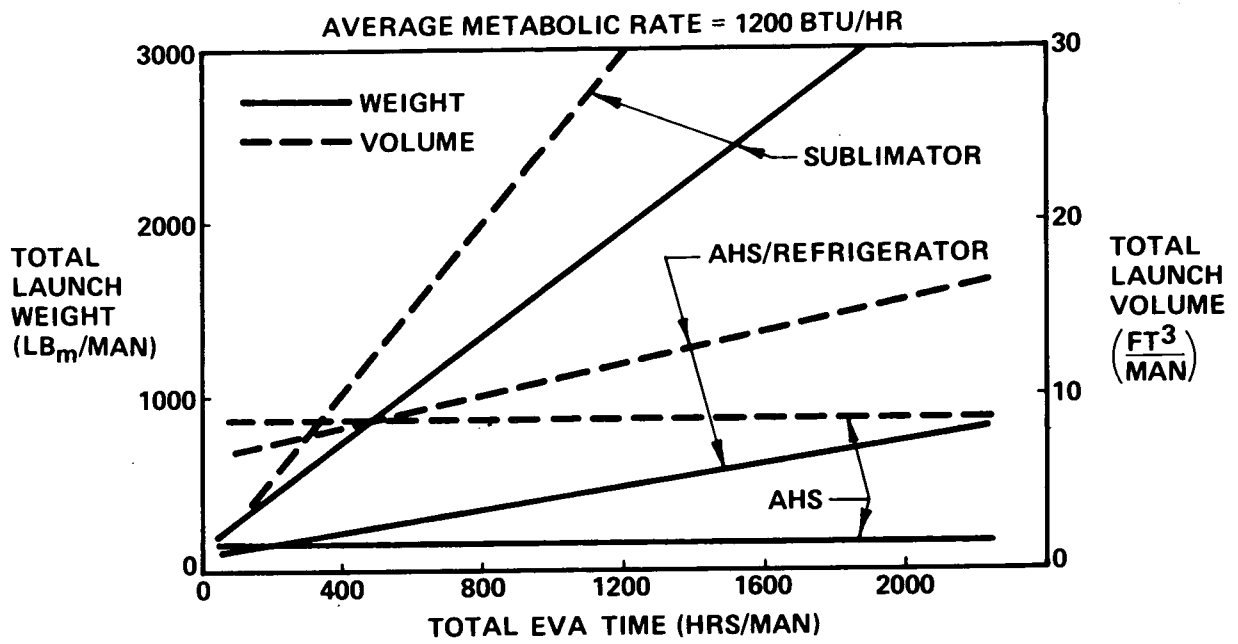


FIGURE 10 AEPS THERMAL CONTROL SUBSYSTEM SIZE COMPARISON-TOTAL LAUNCH WEIGHT AND VOLUME

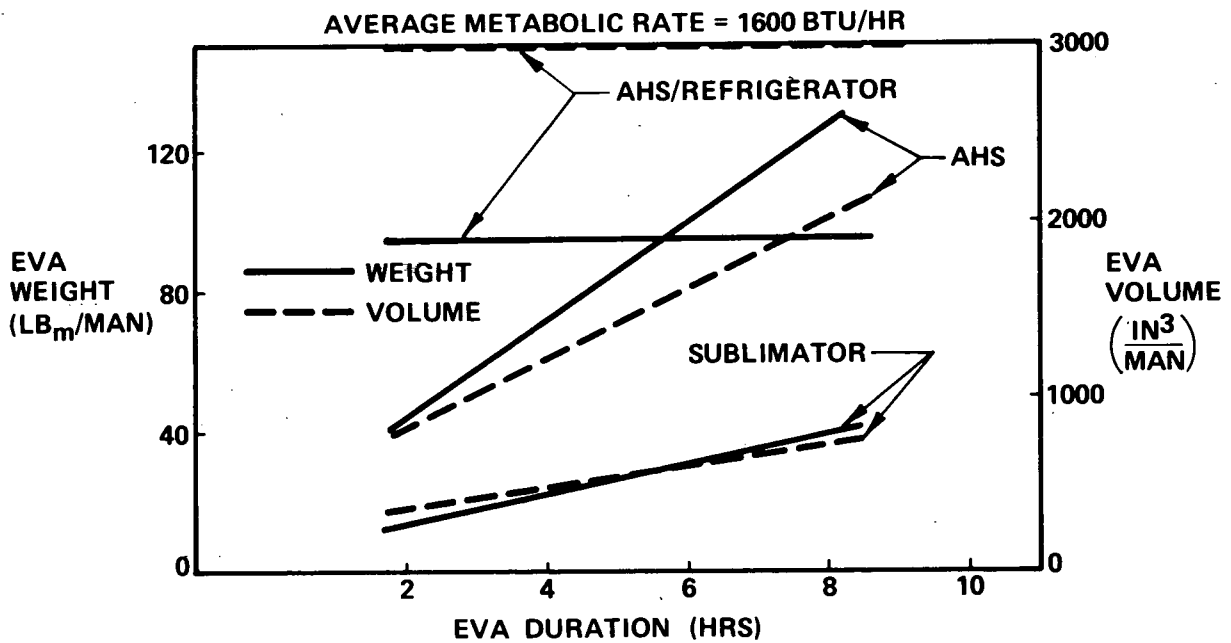


FIGURE 11 AEPS THERMAL CONTROL SUBSYSTEM SIZE COMPARISON-EVA WEIGHT AND VOLUME

imposes an extremely large penalty for any mission requiring numerous EVA's. The weight and volume of the AHS/refrigerator system increases with the number of EVA hours, because of the assumption that 30% of the EVA duration is spent off the umbilical, thus requiring the system to expend some water on each EVA. If it were assumed that the umbilical could be used 80% of the time, no water would be expended on a nominal EVA and the AHS/refrigerator would become the lightest weight thermal control system. It was assumed for the simple AHS system, that no expendable penalty was assigned to this system. Figure 11, which shows weight as a function of individual EVA duration, indicates that the rate-limited refrigeration system size does not change with increased EVA duration while the size of the capacity limited systems increases.

4.4.6 Thermal Control Subsystem Recommendations

The two most promising heat rejection subsystems for missions requiring more than 20 EVA hours are the modular AHS system and the refrigerator with AHS "Top-Off". Both systems offer closed heat rejection at a penalty in EVA weight. A fundamental difference between the two is the module vs umbilical approach. The choice of which system is optimum for a particular mission can only be made at the detailed mission planning stage.

In addition to these primary heat rejection systems, several concepts were identified that would either reduce the AEPS heat load, or improve the primary system performance:

(1) The first is the advanced LCG discussed briefly in Section 4.4. A preliminary analysis indicates that a more comfortable LCG that is a more effective heat exchanger can be produced with a modest development effort. The advantages of this LCG are increasing the wearer comfort and increasing the temperature potential for heat rejection.

(2) A second concept is the integration of a fusible material directly into the suit for an orbital EVA. The thermal environment changes rapidly in low earth orbit and a suit incorporating a "Quilt-Like" pattern of paraffin material, could be used. Materials are available that would change phase at about 80°F and the use of this suit would tend to stabilize the suit at the phase change temperature. This would increase the net heat leak from about -150 BTU/hr to as much as -1000 BTU/hr. This would significantly reduce the heat load on the primary AEPS system without introducing the problems that accompany concepts such as controllable heat pipe suits, etc.

(3) Similarly, for lunar surface EVA, the insulating overcoat principle used for Gemini EVA's can be applied. This would consist of a basic, relatively uninsulated EVA suit that could reject a large fraction of the metabolic heat at night or at low sun angles. An insulating overcoat would cover this suit to minimize the heat leak into the system for daytime operation.

4.5 Humidity Control

Humidity control is usually achieved with a condensing heat exchanger, both in commercial and aerospace applications. In this technique, the air is brought into contact with a cooling coil which is at or slightly below the desired air dew point temperature. Sufficient moisture is condensed out of the process air to reduce the dew point to the cooling apparatus temperature. In spacecraft, the zero-gravity environment requires that a water separation device be used to remove the water droplets from the air stream. A centrifugal device such as an elbow is normally used for this purpose. A transport system, such as a wick system, is required to remove the water from the separation device to a storage container.

The above system may present two problems in an AEPS.

(1) The wick provides an excellent medium for bacterial growth

(2) Some potential regenerable heat rejection systems may not provide a cooling apparatus temperature low enough to yield the required atmosphere dew point temperature.

In this latter case a desiccant system can be employed, the most likely candidates being:

- (1) Silica Gel
- (2) Activated Alumina
- (3) Lithium Chloride
- (4) Molecular Sieve

The amount of water which must be removed from the AEPS atmosphere is about 3.7 lbs per mission, at most. This amount is small enough so that regeneration of the system during a mission would not be required, though regeneration by vacuum venting of the dessicants is possible. Any of the systems can be readily regenerated in the primary base or shelter, thus recovering the water.

In this study a condensing heat exchanger was assumed for humidity control when the heat rejection system could supply 40°F cooling to the gas stream, and a silica gel dessicant system was assumed for systems that operate at a higher cooling temperature.

4.6 Power System

The AEPS life support system requires a power system to drive it; in this study an investigation into power systems was accomplished to identify power sources which might be available in the next decade.

4.6.1 AEPS Power Requirements

The anticipated minimum power demands on an AEPS are:

(1) Ventilation gas circulation	25 watts
(2) Liquid coolant circulation	10 watts
(3) Controls, instrumentation and communications	10 watts
	<hr/>
	45 watts

for a total of 45 watts, and a minimum total energy requirement of 360 watt-hour. This is comparable to the requirements for the current Apollo PLSS. Many potential life support systems, such as a Bosch reactor or a vapor compression refrigeration system have power requirements far in excess of the minimum values listed.

4.6.2 Candidate Power Supply Systems

Potential power sources for AEPS can be divided into four functional categories:

- (1) Battery Systems
- (2) Fuel Cells
- (3) Nuclear Systems
- (4) Solar Panels

Each of these systems is discussed in the following sections.

4.6.3 Battery Systems

Battery systems are usually classified as primary and secondary; the distinction being that primary batteries are not rechargeable.

Primary batteries provide a large power density for a short duration; however, the nature of the AEPS mission makes the secondary, or rechargeable, battery more promising.

Secondary batteries are regenerated by flowing electric current into the battery to reverse the battery discharge reaction. Since the reaction is not completely reversible, there is a maximum number of discharge cycles before the maximum voltage which the battery can produce falls below the minimum allowable value. In addition, the likelihood of battery failure increases with the number of discharges. The depth of discharge is the significant parameter in the recharge life of the battery; usually sixty percent nominal depth of discharge is taken as a reasonable compromise between battery reliability, and size and weight.

For an AEPS application the most significant battery parameters are the mass and volumetric power densities. Table XIV gives a comparison of these parameters plus cycle lifetime for several batteries, including the common automobile-type lead-acid battery.

CELL TYPE	POWER DENSITY ($\frac{\text{WATT}}{\text{LBM}}$)	ENERGY DENSITY ($\frac{\text{WATT-HR}}{\text{LBM}}$)	THEORETICAL ENERGY DENSITY ($\frac{\text{WATT-HR}}{\text{LBM}}$)	VOLUMETRIC ENERGY DENSITY ($\frac{\text{WATT-HR}}{\text{IN}^3}$)	LIFETIME NO. CYCLES (60% DISCHARGE, 25°C)
LEAD-ACID	14	10-12	115	2	400
Ni-Fe	18	16	35	1.1	3000
Ni-Cd	20	18	107	1.0	2000
Ag-Zn	70	45	208	5	300
Ag-Cd	60	56	120	3.7	3000
Li-CuCl ₂	70	160	503	5	—
Li-CuF ₂	—	200	750	4	—
Li-Se	—	164	575	3.5	—
Na-S	100	135	543	5.7	—
Na-Bi	36	18	132	1.3	500
Li-Te	127	82	490	5.9	—

TABLE XIV BATTERY SYSTEM PERFORMANCE PARAMETERS

The silver-zinc (Ag-Zn) and Silver-Cadmium (Ag-Cd) batteries are commonly used in aerospace applications. The advanced sodium and lithium batteries are currently in development, and improvements in the performance of these batteries should be anticipated.

Battery systems are well suited to the AEPS application since they offer acceptable power levels with low weight and volume and they can be regenerated.

4.6.4 Fuel Cells

Fuel cells are very similar to batteries in principle in that electrical energy is produced by a chemical reaction. However, fuel cells generally use externally stored reactants which produce a waste product, so the cell will continue to operate as long as reactants are supplied. The tanks, delivery lines, valves, etc. associated with the reactants tend to make the fuel cell more complicated than a battery. The relative complexity of the fuel cell system with the attendant loss of reliability

results in the fuel cell having no advantage over batteries for AEPS unless significantly higher AEPS power requirements are defined.

Hybrid fuel cell systems which could be combined with life support functions such as carbon dioxide control are possible, but appear to offer little advantage for an AEPS.

4.6.5 Nuclear Power Systems

Nuclear Power Systems use nuclear reactions as a heat source and convert the thermal energy to electricity by various means, primarily:

- (1) Thermoelectrics
- (2) Thermionics
- (3) Dynamic machines

The first two of these systems have characteristically low conversion efficiency, and the last involves a considerable amount of rotating machinery. These factors tend to make nuclear systems non-competitive for an application with low power and energy requirements such as AEPS.

4.6.6 Solar Cells

Solar cells convert sunlight directly into electrical energy. Usually some sort of power regulation equipment is required with a solar cell system. If the system is shadowed part of the time, such as in earth orbit, then a battery system is required for continual power delivery.

Improvements in solar cell design can be anticipated; and yields of 40 watt/lb, and 8 to 17 watt/ft² (at one astronomical unit) for cadmium sulfide (CdS) thin film cells and silicon cells, respectively, seem reasonable to expect. This assumes that the cell array is aligned normal to the solar vector; off-alignment will require that the cell array be larger. Efficiency of the cell array is strongly dependent on temperature, and temperature control on the lunar surface, for instance, would be difficult to achieve.

The light weight and no expendable or recharge requirement characteristics of the solar cell make it attractive; however, area and alignment requirements of the cell array make solar cells impractical for a system transported on a man's back. The solar cell is attractive for vehicle power systems.

4.6.7 Selected System

Batteries were selected as the power source for AEPS; this is based on the premise that the total energy requirement is no more than 1 kw-hr for an 8-hour mission.

Lithium-halide batteries were selected as the power supply subsystem for the total system weight evaluations. The values of 200 watt-hr/lb and 4 watt-hr/in³ were assumed for the battery; this represents performance that can now be achieved with lithium-halide batteries (specifically the Li-CuF₂ battery).

Figure 12 shows the weight and volume of the AEPS power system as a function of power requirement, including the allowance for 60% depth of discharge in a nominal mission (as discussed in Section 4.6.3).

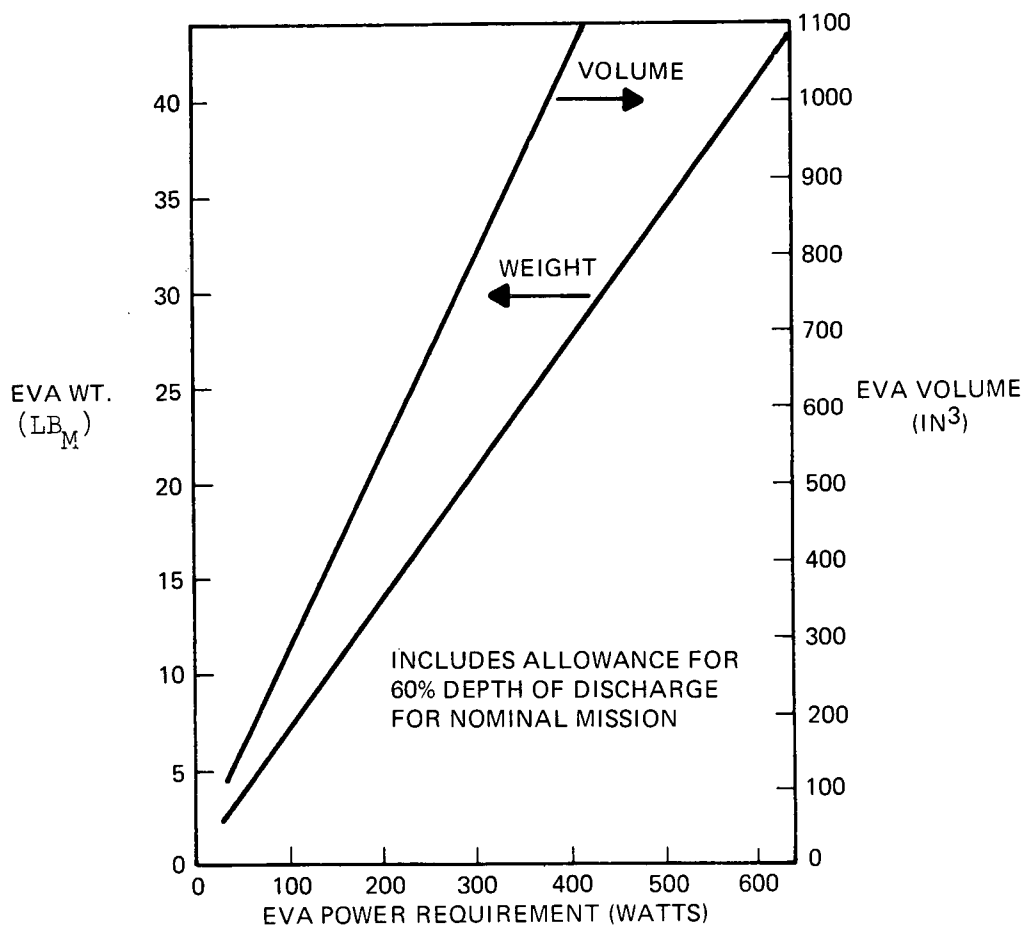


FIGURE 12 POWER SYSTEMS WEIGHT AND VOLUME SUMMARY

5.0 SUBSYSTEM CONCEPT INTEGRATION

The most promising subsystems for performing the AEPS life support functions can now be combined for consideration at the total system level. Table XV shows the candidates remaining after the subsystem "trade-off" process discussed in Section 4.0.

OXYGEN SUPPLY		CO ₂ CONTROL	THERMAL CONTROL
ORBITAL EVA			
I	HIGH PRESSURE GAS	1 - LiOH	A - EVAPORATOR
II	UMBILICAL TO BASE	2 - VACUUM DESORBED SOLID AMINE	B - AHS WITH UMBILICAL TO LARGE AHS
		3 - Mg(OH) ₂	C - UMBILICAL TO BASE
		4 - KOH	
		5 - UMBILICAL TO BASE	
LUNAR EVA			
I	HIGH PRESSURE GAS	1 - LiOH	A - EVAPORATOR
		2 - VACUUM DESORBED SOLID AMINE	D - AHS
		3 - Mg(OH) ₂	E - AHS WITH UMBILICAL TO REFRIGERATOR
		4 - KOH	
MARS EVA			
I	HIGH PRESSURE GAS	1 - LiOH	A - EVAPORATOR
		3 - Mg(OH) ₂	D - AHS
		4 - KOH	F - AHS WITH UMBILICAL TO RADIATOR

TABLE XV FINAL CANDIDATE SUBSYSTEMS

The suitability of the subsystem concepts for different applications has been somewhat arbitrarily decided. For example, an umbilical to the base could be used to supply life support for any AEPS mission. However, orbital EVA's will most probably be conducted in the vicinity of a base while surface EVA's will generally be more wide ranging. An umbilical to the base could be used for any AEPS application where long periods are spent in the immediate vicinity of the base.

It was assumed that a large AHS system would probably not be used for surface operations due to its mass. This system is very compact, however, and it would be well suited for mounting on a small, powered surface transporter (LRV-type).

The modular AHS system was not considered for orbital use because of potential difficulty in changing AHS units in "zero-g". However, if the fresh AHS packs were stored in a fixed locker in the vehicle with exterior access, the crewman might be spared some of the difficulty of changing packs without losing them. Furthermore, if the average orbital EVA duration was only 4-5 hours the fusible heat sink could be integrated into the backpack and/or suit, since AEPS weight is less critical in "zero-g" than on a planetary surface.

Similarly, the refrigeration or radiator systems were not considered for orbital use because of potential problems with maneuvering any system that required a deployed radiator. If this system was integrated with a small maneuvering work platform, this difficulty would be significantly alleviated.

LiOH, $Mg(OH)_2$, and KOH systems for CO_2 control can be used on any AEPS mission. However, the vacuum desorbed amine system is not suitable for a Mars EVA due to the relatively high CO_2 partial pressure in the atmosphere.

All of these subsystems are suitable for integration with any other subsystem into a total AEPS system. There are twenty such combinations of potential AEPS systems. All of these systems are assumed to use a lithium-halide battery for power supply, with activated charcoal for trace contaminant control, and either a desiccant or condensing heat exchanger for humidity control, depending on the temperature level of the heat rejection system.

Figure 13 shows the total launch weight, including regeneration equipment base penalties, expendables, etc. as a function of the number of two man EVA's for the 9 most promising systems considering the total system heat load to be 1200 BTU/hr. Figure 14 gives the same information for a total heat load of 2000 BTU/hr. These total system heat loads correspond to metabolic rates of 1000 BTU/hr and 1700 BTU/hr, respectively, with no heat leak; or higher metabolic rates with negative heat leak, etc. The total system heat load is used as a parameter rather than metabolic rate since this is the factor that determines the heat rejection expendables, and it is a function of environment as well as metabolic rate. Therefore, the use of total heat load allows these curves to be independent of the environment so long as the total heat load equals the assumed values.

The completely regenerable systems show a weight increase with total EVA time because of suit gas leakage. Also, the closed heat rejection systems which require an umbilical may show a further increase in weight with total EVA time because of the arbitrary assumption that only 70% of each EVA would be spent on the umbilical; the remaining 30% would be spent on a supplemental, or "top-off" heat rejection system which may require some expendables.

TOTAL HEAT LOAD = 1200 BTU/HR

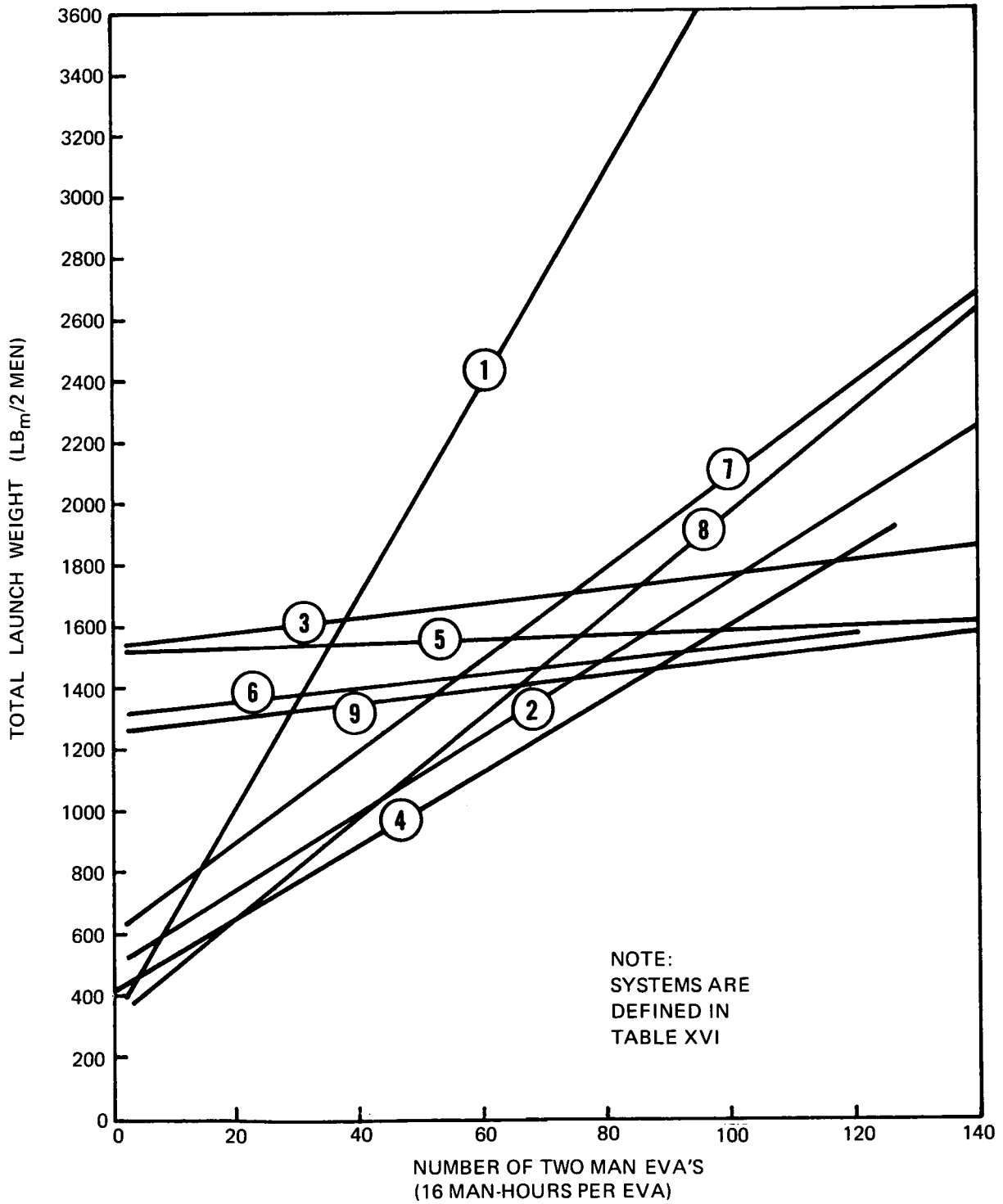


FIGURE 13 AEPS TOTAL SYSTEM LAUNCH WEIGHT VS. NUMBER OF EVA'S - 1200 BTU/HR HEAT LOAD

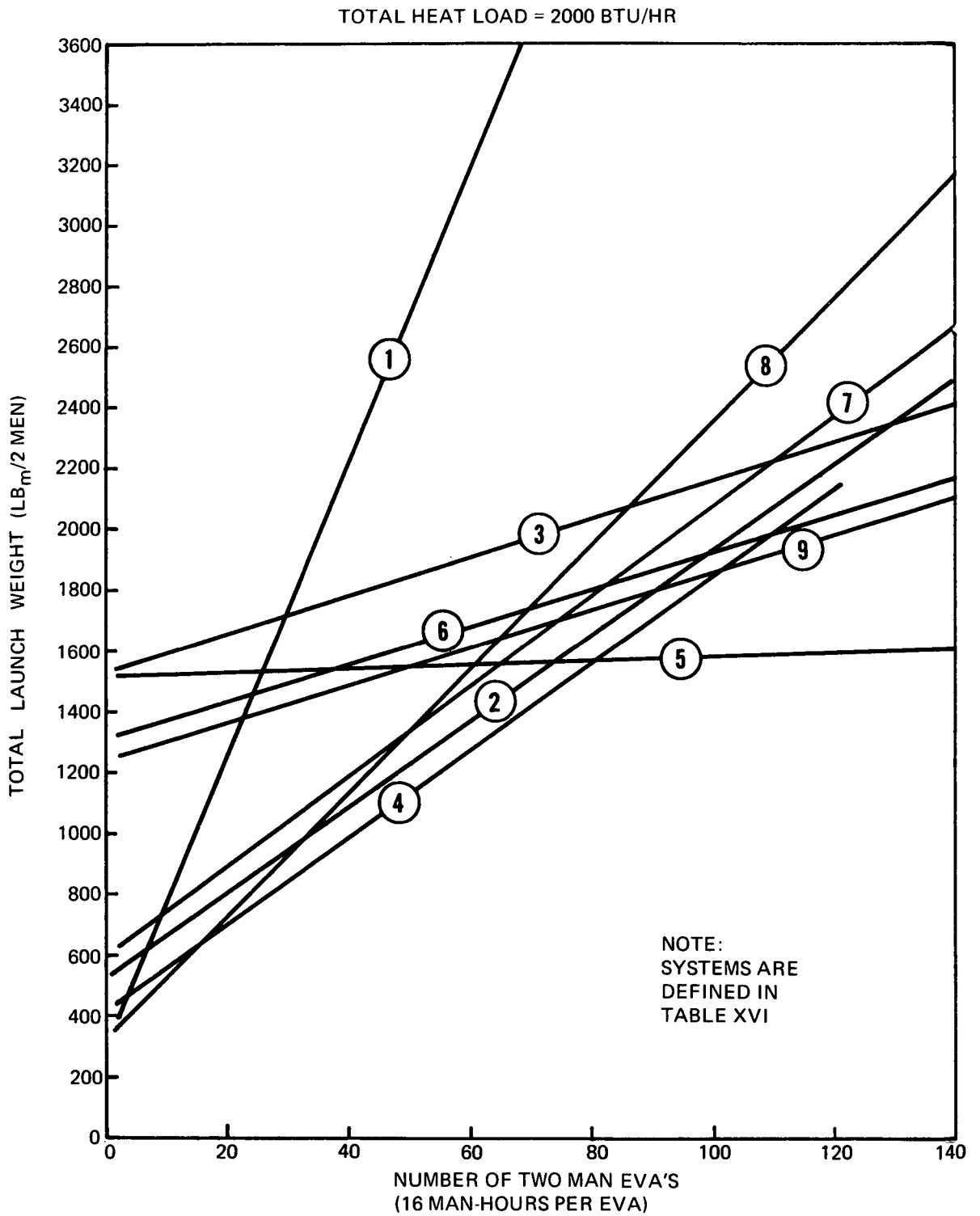


FIGURE 14 AEPS TOTAL SYSTEM LAUNCH WEIGHT VS. NUMBER OF EVA'S – 2000 BTU/HR HEAT LOAD

The ordinate intercept of these curves is the total system weight, including all base equipment and penalties, EVA packs and spares, etc., but excluding the expendable weight. The slope of each curve gives the system expendable weight in lb_m per 2 man EVA.

The system weights were based on 2 man EVA events because of the groundrule that safety requirements would dictate that at least two men be involved in each EVA event. Increasing the number of men participating in an EVA event reduces the amount of support equipment needed for regenerable portable life support equipment on a per man basis.

Total system weight calculations showed that system combinations such as $Mg(OH)_2$ combined with an evaporator are not competitive for any number of EVA's (not shown on Figures 13 and 14). Thus, ten of the systems were eliminated on a total weight basis. The general trend shown by the figures is that the expendable PLSS type system is lightest for less than about 5 EVA. Between approximately 5 and 100 EVA's an expendable or partially regenerable CO_2 control system, with a closed or semi-closed heat rejection system is superior, while a closed CO_2 system is required for more than 100 EVA's.

The nine remaining systems must now be compared on a more detailed basis. Table XVI shows some of the required parameters for each of the systems. $Mg(OH)_2$ was chosen for final system integration over KOH because there is less uncertainty about the technical feasibility of the system. The KOH system has a potential advantage in pack weight and volume so that if the system feasibility could be demonstrated, it would probably be the superior system.

As shown in Table XVI, some of the subsystems have specific mission applications so that total system combinations employing these subsystem concepts are not applicable to all AEPS missions.

A PLSS-type system with improved LiOH utilization and reusability is suitable for all potential AEPS missions. However, this system is only competitive for less than about 10 EVA's so that it would not be used for long-term lunar or Mars missions involving many EVA's. The large AHS/umbilical support system could be used on any mission. It was assumed that it would not be used for surface EVA due to its large mass but if a powered transporter were assumed, it would be an attractive system due to its compact size. Similarly, the refrigeration system could be used for orbital or Mars surface missions but it is not required for Mars, as discussed earlier, and the difficulty of maneuvering a deployed radiator limits its use for orbital missions.

Systems 2 and 4 are the least desirable of the remaining systems, due to the large pack weight and volume required for the amine system. This method of CO_2 control has inherent reliability problems when applied to an AEPS size unit. These problems are sufficient to make this system undesirable unless it can be shown that considerable advantage can be taken of the development effort already expended on solid amine systems for space station use.

SYSTEM NO. AND DESCRIPTION	PACK WT. (LBM/MAN)	PACK VOL. (IN ³ /MAN)	EVA SUPPORT WEIGHT (LBM/2 MEN)	EVA SUPPORT VOLUME (IN ³ /2 MEN)	TOTAL EVA WEIGHT (LBM/2 MEN)	TOTAL EVA VOLUME (IN ³ /2 MEN)	SUITABLE MISSION DURATION (NO. OF EVA)	AEPS APPLICANT *
1 - IMPROVED PLSS	120	2650	0	0	240	5,300	< 10	⊕ ☾ ♂
2 - AMINE/AHS WITH UMBILICAL TO LG. AHS	150	4940	294	7020	594	16,900	10 - 100	⊕
3 - Mg (OH) ₂ /AHS WITH UMBILICAL TO LARGE AHS	144	3900	294	7020	582	14,820	> 100	⊕
4 - AMINE/AHS/ REFRIGERATOR "TOP-OFF"	150	4940	131	4370	431	14,250	10 - 100	☾
5 - Mg (OH) ₂ /AHS	134	3600	203	4750	471	11,950	> 100	☾ ♂
6 - Mg (OH) ₂ /AHS/ REFRIGERATOR "TOP-OFF"	144	3900	131	4370	419	12,170	> 100	☾
7 - LiOH/AHS	108	2520	203	4750	419	9,790	10 - 50	☾ ♂
8 - LiOH/AHS RADIATOR "TOP-OFF"	117	2820	76	2990	310	8,630	10 - 50	♂
9 - Mg (OH) ₂ /AHS/ RADIATOR "TOP-OFF"	144	3900	76	2990	364	10,790	> 50	♂

* ⊕ - EARTH ORBIT EVA
☾ - LUNAR EVA
♂ - MARS EVA

TABLE XVI INTEGRATED AEPS SYSTEM EVA WEIGHT AND VOLUME SUMMARY

Table XVI and Figures 13 and 14 illustrate that a decrease in total system weight, by reducing expendables, can only be accomplished by an increase in the EVA mass and volume. It is possible to integrate non-expendable life support systems within the weight and volume constraints of a backpack, with the exception of the heat rejection system.

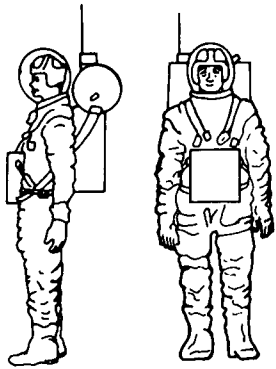
The two methods of using a small transporter for AEPS support, i.e. modular or umbilical approach, were discussed earlier. It was found, that the modular AHS system is heavier than the refrigerator, umbilical system, 203 lb_m per 2 men vs 131 lb_m per 2 men and that EVA time is required to change modules. However, the system is more compact, since no radiator is required, and therefore, it may be easier to transport. In addition, no mobility is sacrificed by requiring an umbilical and the system has the capability to operate for the full EVA duration, without support, by employing the expendable mode of operation. The refrigeration system has an EVA weight of 131 lb_m per 2 men and the only base requirement is a battery charger and a 200 watt (100 lb_m) recharge power penalty.

A heat exchanger is included between the LCG loop and the umbilical fluid to preclude the possibility of an umbilical failure causing a loss of all cooling. This system is probably best suited for applications where a powered (LRV Type) transporter is assumed. The refrigerator/radiator could be easily integrated with the transporter and it could be used while riding on the transporter and for operations in its immediate vicinity. The inclusion of a fusible AHS heat sink into the pack allows 1-2 hours operation, without the umbilical, without consuming water. If more non-umbilical time is required, the EVA can be continued with no loss in capability, simply by switching the AHS to the expendable mode.

Several conceptual backpack designs were produced to demonstrate that the regenerable thermal control and CO₂ control subsystems could be integrated with the other AEPS subsystems, into a practical pack system.

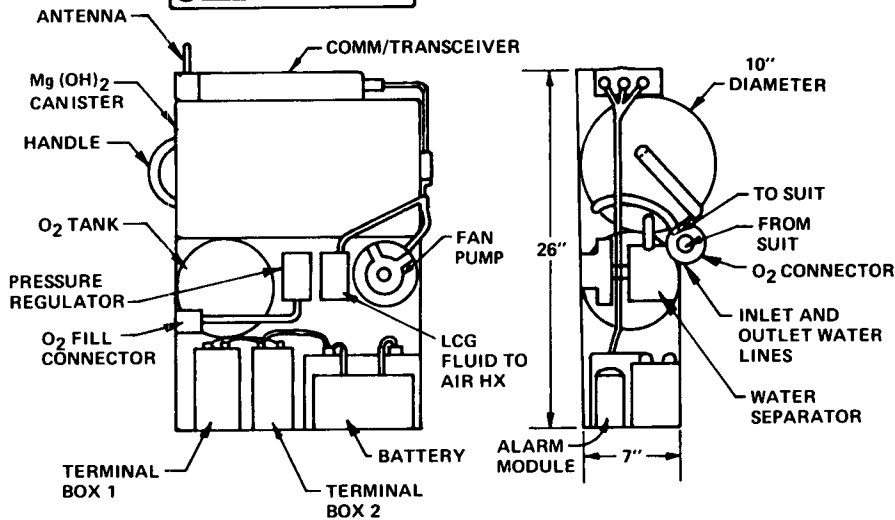
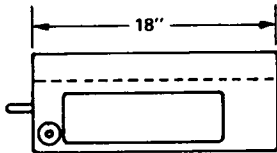
Figure 15 illustrates a system using an Mg(OH)₂ canister for CO₂ control with a modular AHS carried in a chest pack. This chest pack also contains the backpack controls, quantity indicators, and warning lights similar to the PLSS Remote Control Unit (RCU). The chest mounting of the modular AHS was chosen because it facilitates module replacement. The large volume of the Mg(OH)₂ canister is primarily responsible for the large bulk of the backpack. However, the total weight of the system is only about 25 lb_m greater than the -7 PLSS. This system has the capability to operate for 1-2 hours without requiring any expendables or replacement modules and a full 8 hours by utilizing the AHS evaporation mode.

The system shown in Figure 16 is similar but a heat exchanger and umbilical are included to connect to a refrigeration system. An AHS chest pack is also included to allow 1-2 hours of non-expendable operation

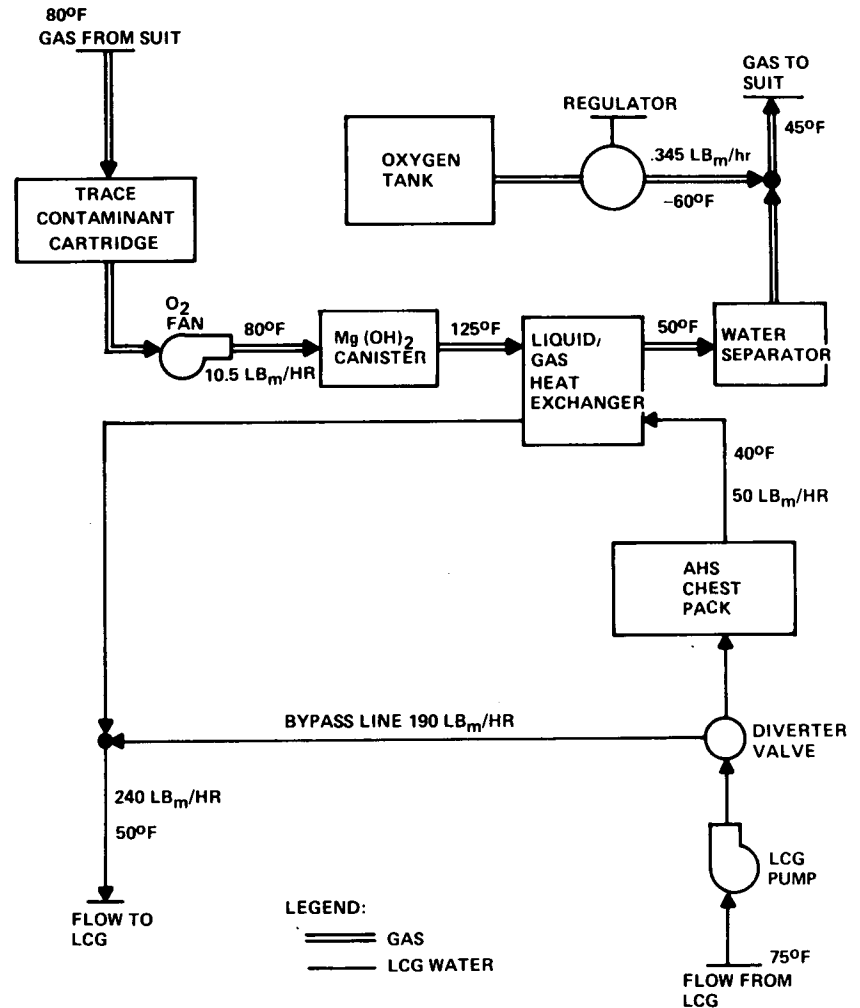


WEIGHT SUMMARY

BACKPACK	
OXYGEN BOTTLE	10.40
Mg (OH) ₂	38.90
TRACE CONTAMINANT	0.30
BATTERY	10.50
REMAINDER	47.82
CHEST PACK	
RCU	5.64
AHS	30.00
TOTAL	143.56 LB_m

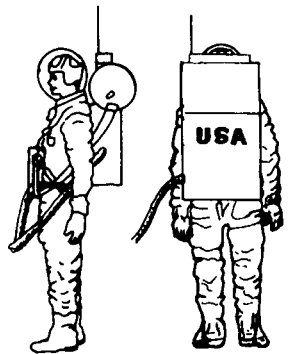


SYSTEM SCHEMATIC



LEGEND:
 ——— GAS
 ——— LCG WATER

FIGURE 15 BACKPACK WITH MAGNESIUM HYDROXIDE CARBON DIOXIDE CONTROL & CHEST PACK AHS HEAT REJECTION SYSTEM



WEIGHT SUMMARY

BACKPACK	
OXYGEN BOTTLE	10.40
Mg(OH) ₂ REACTOR	39.00
TRACE CONTAMINANT	0.30
BATTERY	10.50
AHS	30.00
STD & MISC	47.30
<hr/>	
CHEST PACK	
RCU	5.6
<hr/>	
TOTAL (NOT INCL. UMBILICAL)	143.1

61

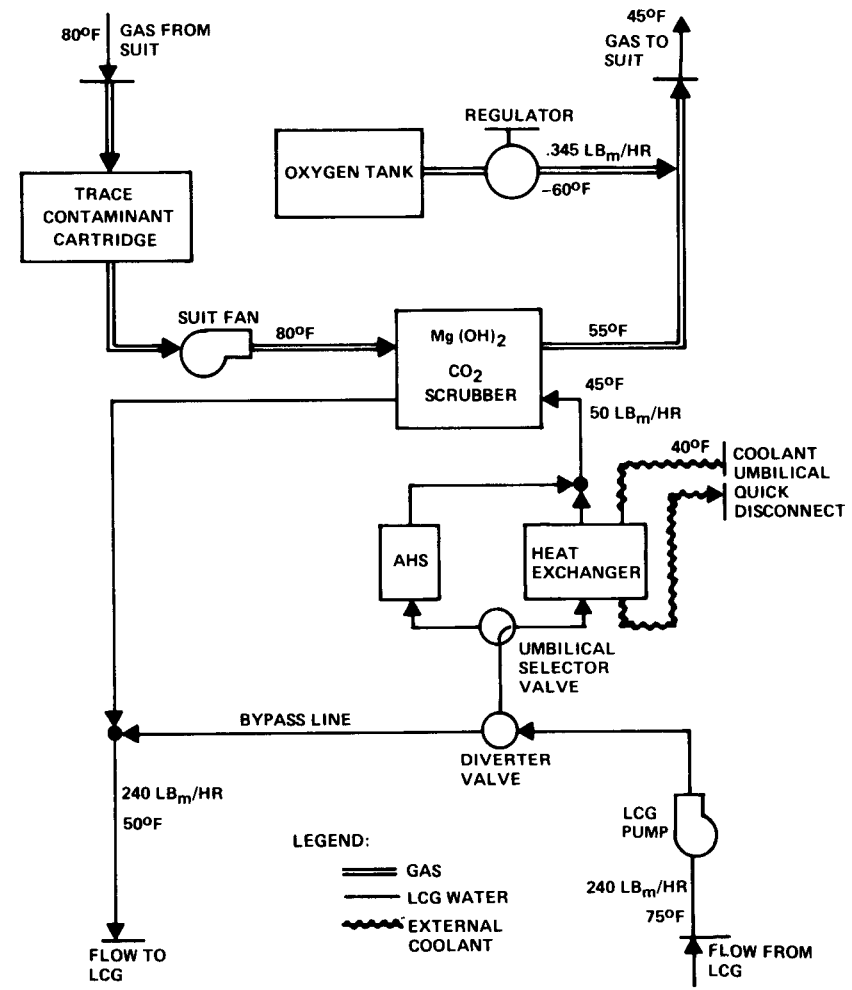
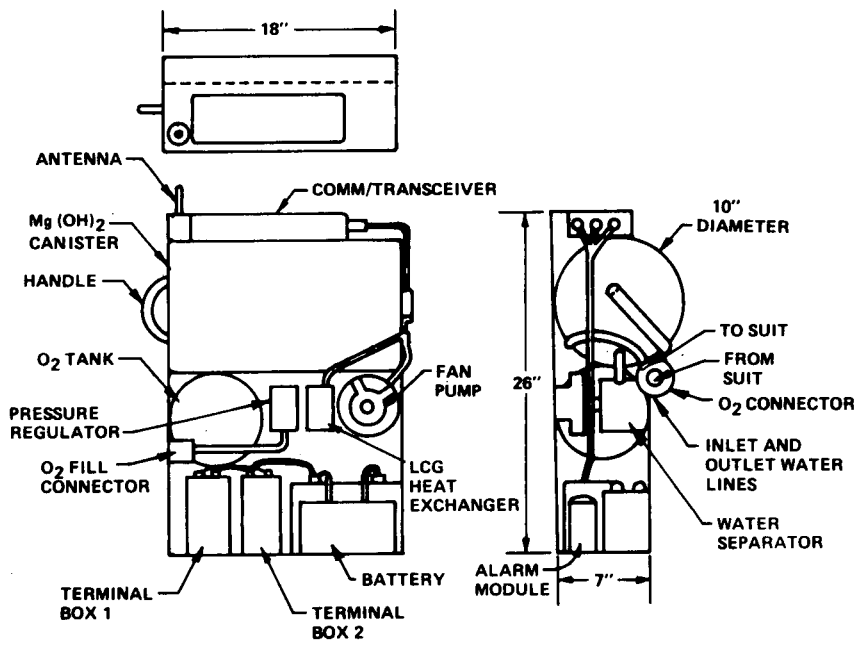


FIGURE 16 BACKPACK WITH MAGNESIUM HYDROXIDE CARBON DIOXIDE CONTROL & AHS/REFRIGERATOR HEAT REJECTION SYSTEM

without the umbilical. Since the AHS is not replaced during the EVA with this system, it could be integrated into the backpack. This pack weighs more than the modular AHS pack because of the requirement for a heat exchanger and umbilical quick-disconnects.

Figures 17 and 18 summarize the weight and volume requirements for the four most promising AEPS total systems. The expendable LiOH/sublimator system is shown to have the smallest total launch weight and volume for less than about 50 EVA hours per man. System 7, which uses expendable LiOH for CO₂ control coupled with the regenerable AHS thermal control subsystem, offers a large total weight saving over the completely expendable system. This system is a logical interim step toward the development of a fully regenerable system.

A system using a solid amine CO₂ control system with an AHS is shown to have the smallest total launch weight from about 50 to 1300 EVA hours. However, the weight of the systems using a closed Mg(OH)₂ CO₂ control subsystems is determined to a large part by the base regeneration penalties and as previously discussed these penalties and assumptions such as the respiratory quotient, etc., were deliberately chosen to be conservative. Thus, the region where the amine system is the lightest may be considerably smaller than shown in Figure 17.

Figure 18 shows the EVA weight for the same four systems as a function of EVA duration. The weight carried by the man is indicated by the dashed lines while the solid lines show the total EVA weight. This weight includes fresh AHS modules with their storage container or a refrigeration system along with the pack weight. This figure shows that the pack weight is relatively independent of the EVA duration while the total EVA weight of a system using AHS thermal control changes considerably since about 10 lb_m of ice are required for each EVA hour.

Figures 17 and 18 illustrate the conclusion that a large saving in total system weight by utilizing regenerable subsystem is possible only by increasing the weight of the EVA system. In order to minimize the EVA transportation difficulties, a large part of this weight is separate from the man and he is supported by means of a cooling umbilical or with replaceable AHS modules. Thus, the weight of the pack that the man must carry is only slightly increased over the weight of an expendable "PLSS-type" system. This is felt to be the most promising approach to providing a fully regenerable EVA life support system with minimum encumbrance.

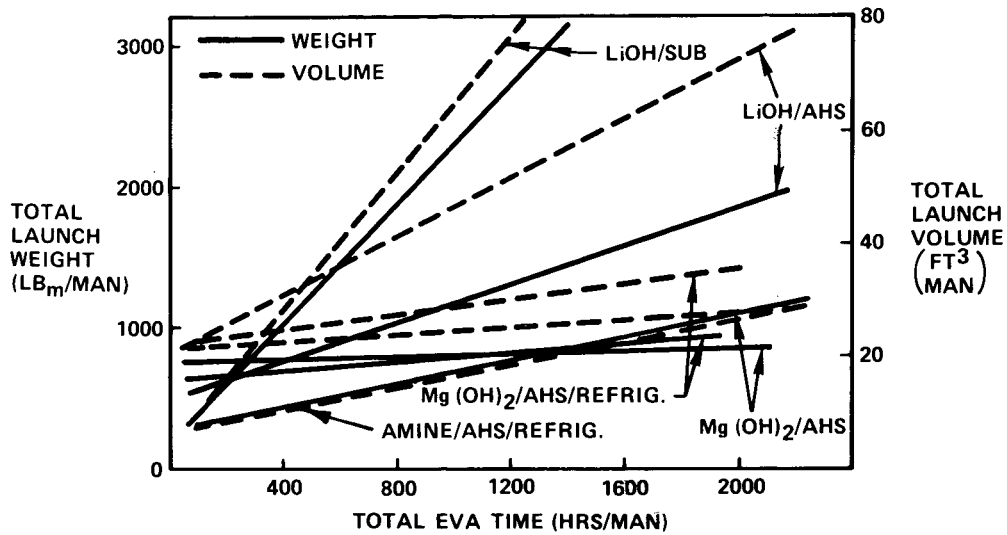


FIGURE 17 AEPS COMPLETE SYSTEM SIZE COMPARISON – TOTAL LAUNCH WEIGHT AND VOLUME

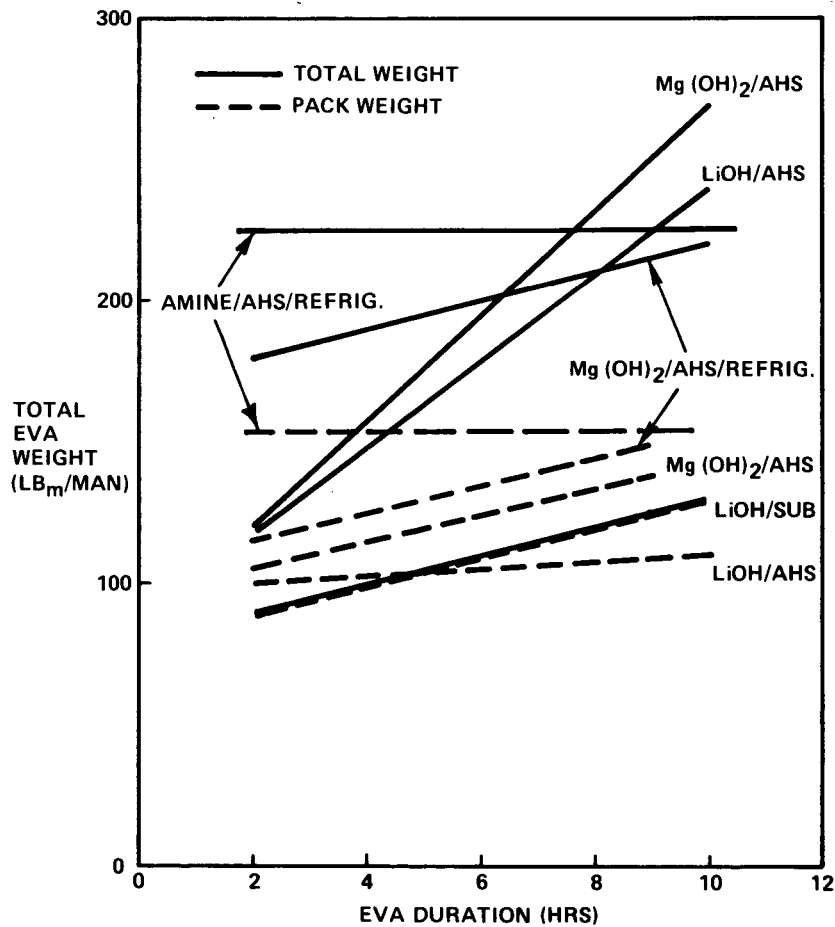


FIGURE 18 AEPS COMPLETE SYSTEM SIZE COMPARISON – EVA WEIGHT

6.0 CONCLUSIONS AND RECOMMENDATIONS

The improved (68% conversion efficiency) Lithium Hydroxide (LiOH) carbon dioxide control concept is best for missions involving up to 500 hours each of EVA time for two crewmen. Beyond this point the thermally regenerable Magnesium Hydroxide ($Mg(OH)_2$) concept is favored. The trade point is significantly influenced by the base power penalty since slightly over 50% of the $Mg(OH)_2$ total launch weight is power penalty for reducing the carbon dioxide which is produced during the EVA to recover the oxygen; 25% is for energy penalty associated with regeneration of the $Mg(OH)_2$; and only the remaining 25% is actual hardware weight.

The water evaporator expendable thermal control concept is the best choice for missions involving up to 20 hours of EVA time each for two crewmen. Beyond this point the regenerable thermal control systems are superior from a total launch system standpoint; although they do involve the use of a transporter to support the AEPS design mission. The most favorable concept is the AHS in some form; it has simplicity, low total launch weight, and the weight and volume actually carried by the crewman is less than for the water evaporator expendable concept. For planetary and surface missions a transporter to supply additional AHS modules is required for the AEPS design mission. The crewman has complete freedom of movement, since he is not tied to the transporter by an umbilical but some useful EVA time is sacrificed in replacement of AHS modules. It is not mandatory that the crewman remain near the transporter, or that he replace AHS modules, since he can use the AHS in the water evaporator mode, in which case there is an ample supply of water to accomplish the AEPS design mission. For use in orbital operations the design mission duration will probably be less than the AEPS design mission duration of 8 hours, thus a single, large fusible heat sink device may be attractive. It is also possible that the design metabolic rate used for planetary missions will be less than the 1600 BTU/hr used for the AEPS design EVA, and this will make the AHS more attractive since less frequent replacement of AHS modules would be required, and fewer AHS modules would be carried.

The thermal control concept of the refrigeration machine with an AHS for "top-off" is attractive for lunar surface operations. It has the disadvantages of a requirement for a coolant umbilical, and relatively high subsystem complexity. For Mars surface operation the refrigeration machine could be replaced by a simple space radiator subsystem. In orbital operations or on Mars the space radiator mounted on the transporter could be replaced by an integral suit radiator, with an increase in the required capacity of the "top-off" system.

The following general conclusions were reached in the AEPS study:

- (1) Regenerable Portable Life Support Systems for use in EVA are feasible.

(2) The most promising approach to regenerable portable life support subsystems involves regeneration at the primary base or shelter.

(3) Regenerable portable life support subsystem concepts offer large total launch weight savings at the expense of EVA weight and volume.

Recommendations for future development work are given in Table XVII, for both primary and secondary efforts. The highest priority subsystem concept recommendations are:

(1) Develop the AHS concept to provide a regenerable thermal control subsystem, which will be beneficial on missions involving more than 20 hours of EVA time.

(2) Develop the improved lithium hydroxide (68% conversion efficiency) carbon dioxide control concept, which will be advantageous on missions involving up to 500 hours of EVA time.

(3) Develop the magnesium hydroxide carbon dioxide control system, which will be beneficial on missions involving more than 500 hours of EVA time.

(4) Perform a study to determine the optimum means of executing EVA from a vehicle with a 14.7 psia, two-gas atmosphere.

<u>PRIMARY ITEMS</u>	<u>RECOMMENDATION</u>
(1) ASTRONAUT HEAT SINK (AHS)	DEMONSTRATE FEASIBILITY OF THE AHS CONCEPT AND DETERMINE OPTIMUM METHOD OF INTEGRATION WITH AEPS
(2) Mg (OH) ₂ CO ₂ CONTROL SYSTEM	DEMONSTRATE FEASIBILITY OF AEPS DESIGN AND BASE REGENERATION FACILITY.
(3) LiOH CO ₂ CONTROL SYSTEM	IMPROVE UTILIZATION EFFICIENCY
(4) KOH CO ₂ CONTROL SYSTEM	INVESTIGATE THE CONCEPT FEASIBILITY
(5) PORTABLE REFRIGERATION SYSTEM	DEVELOP HARDWARE FOR PORTABLE LUNAR REFRIGERATION SYSTEM
 <u>SECONDARY ITEMS</u> 	
(a) LCG DESIGN	DEVELOP MORE EFFECTIVE AND COMFORTABLE LCG
(b) HEAT SINK SUIT	INVESTIGATE POTENTIAL BENEFITS AND DESIGN FOR ORBITAL EVA
(c) IMPROVED PLSS	INCREASED REUSABILITY, RELIABILITY, AND EVA DURATION
(d) FLEXIBLE RADIATOR	DEMONSTRATE FEASIBILITY OF FLEXIBLE, OPTICAL SOLAR REFLECTOR RADIATOR
(e) PORTABLE RADIATOR SYSTEM	DEVELOP HARDWARE FOR PORTABLE MARS RADIATOR SYSTEM
(f) UMBILICAL DESIGN	INVESTIGATE DESIGN OF LIGHT WEIGHT FLEXIBLE COOLING UMBILICALS AND DETERMINE MOBILITY RESTRICTIONS
(g) VACUUM QUICK-DISCONNECTS	DEVELOP HARDWARE FOR RELIABLE VACUUM QUICK-DISCONNECTS
(h) VACUUM DESORBED AMINE CO ₂ CONTROL SYSTEM	DEMONSTRATE FEASIBILITY OF BACKPACK SIZE UNIT WITH REQUIRED BED HUMIDITY CONTROL AND RELIABILITY
(i) HIGH PRESSURE O ₂ COMPRESSOR	DEVELOP LIGHT-WEIGHT COMPRESSOR FOR REFILLING EVA O ₂ TANKS AT BASE
(j) EVA THERMAL CONTROL OVERCOAT	INVESTIGATE FEASIBILITY AND POTENTIAL WEIGHT SAVINGS FOR LUNAR EVA
(k) BIOLOGICAL CLEANING	INVESTIGATE METHODS OF STERILIZATION AND CLEANING OF EVA EQUIPMENT FOR LONG TERM, REPEATED USE
(l) LUNAR DUST	INVESTIGATE LUNAR DUST DEGRADATION OF THERMAL CONTROL SURFACES AND DUST REMOVAL TECHNIQUES

TABLE XVII RECOMMENDED AEPS DEVELOPMENT ITEMS

7.0 REFERENCES

- (1) "America's Next Decades in Space - A Report for the Space Task Group", prepared by the National Aeronautics and Space Administration, September 1969.
- (2) "An Integrated Program of Space Utilization and Exploration for the Decade of 1970 to 1980", prepared by Bellcomm, Inc. for the National Aeronautics and Space Administration, 16 July 1969.
- (3) Hudock, R. P., "A/A Report on the National Scene - Space Station: Build the Shuttle First", Astronautics and Aeronautics, AIAA, February 1971.
- (4) Johnsen, Katherine, "Rover Reoriented as Shuttle Complement," Aviation - Week and Space Technology, 22 February 1971.
- (5) "Proceedings of the Winter Study of Uses of Manned Space Flight 1975-1985", Volume II - Appendices, NASA Science and Technology Advisory Committee for Manned Space Flight, NASA SP-196, Dec. 1968.
- (6) RFP A-15999 (AC-30), "Request for Proposal For Advanced Extravehicular Protective System (AEPS)", NASA-Ames Research Center, dated 11 February 1970.
- (7) Chandeysson, P. L., et. al., "Integrated Space Program - Manned Planetary Missions for the 1980's", Oral Briefing to Dr. Paine at NASA Headquarters, prepared by Bellcomm, Inc., 28 July 1969.
- (8) Mansfield, J. M. and R. B. Carpenter, "SLA Mini-Base Concept for Extended Lunar Missions", Volume I, Space Division/North American Rockwell Report SD 70-516, dated September 1970.
- (9) Oral Presentation by R. B. Carpenter, "Lunar Surface Base Complex", Space Division/North American Rockwell Presentation No. 11PD107448, given at NASA-Ames Research Center on 21 January 1971.
- (10) "Space Station Program; Phase B Definition - May Progress Review", PDS 70-232 Space Division/North American Rockwell, Presented to NASA-MSD on 14 May 1970.
- (11) "Space Station Program; Phase B Definition - NASA-Headquarters Technical Review", PDS 69-124, Space Division/North American Rockwell, 30 December 1969.
- (12) Borentz, J. E., "Large Space Station Power Systems", AIAA Paper No. 68-1034, Presented at the AIAA 5th Annual Meeting and Technical Display, Philadelphia, Pennsylvania on 21-24 October 1968.
- (13) "DC-3 - Space Shuttle Study - Volume II" Prepared by NASA-MSD Engineering and Development Directorate with Support of Flight Operations Directorate, dated 27 April 1970.

References (Cont'd)

- (14) Mandell, H. C., "A Graphical Costing Procedure for Advanced Spacecraft (MASCOT G)", NASA TM X - 58012, dated October 1967.
- (15) Krantweiss, G., "Survey of Aircraft Thermal Control Systems", Technical Report AFFDL-TR-66-44, November 1966.
- (16) "United Aircraft Gets \$14.1 Addition to Contract from NASA", Wall Street Journal, 23 July 1970.
- (17) Hamilton-Standard Engineering Memorandum No. NA-SS-4310, "Apollo Extravehicular Mobility Unit Weight Report", Transmittal of 15 April 1970.
- (18) Nicks, R. F., L. D. Gregory, and R. E. Dyer, "Extra-vehicular Activities System Effectiveness," VMSC Report No. 00.1115, AFAPL-TR-68-135, Vol. III, Dated January 1969. pps. 19 and 20.
- (19) Normyle, W. J., "Shuttle Poses Dominant Challenge", Aviation Week and Space Technology, 22 June 1970, p. 109.
- (20) VMSC Report No. 00.676, "Advanced Orbital Launch Operations", dated November 1965.
- (21) NASA SP-8023, "Lunar Surface Models", 1969.
- (22) NASA SP-8010, "Models of Mars Atmosphere", 1968.
- (23) NASA SP-8020, "Mars Surface Models", 1969.
- (24) Webb, P., editor, "Bioastronautics Data Book", NASA SP-3006, 1964, pp. 174-178, 185.
- (25) ASD-TR-61-162, Part II, "Analytical Methods for Space Vehicle Atmospheric Control Processes", Prepared by AiResearch Manufacturing Co., July 1962.
- (26) NASA CR-1458, "Trade-off Study and Conceptual Designs of Regenerative Advanced Integrated Life Support Systems (AILSS)", prepared by Hamilton-Standard Division for Langley Research Center, January 1970.
- (27) "Chemical Engineering in the Lunar Environment", Chemical Engineering Progress Symposium Series No. 61, Vol. 62, 1966.
- (28) "The On-Site Manufacture of Propellant Oxygen from Lunar Resources", Chemical Engineering Progress Symposium Series, No. 61, Vol. 62, 1966.
- (29) "Lunar Production of Water and Oxygen", Chemical Engineering Progress Symposium Series, No. 61, Vol. 62, 1966.

References (cont'd)

- (30) "Water and Chemical Recovery in a Lunar Environment", Chemical Engineering Progress Symposium Series, No. 61, Vol. 62, 1966
- (31) Freeman, H. E. "Program 631A, Volume IV Technical Report - Experiment D-12, Astronaut Maneuvering Unit", LTV Missiles and Space Division Report No. 335.83, 23 March 1967.
- (32) Curtis, D. L., "Open-Loop Portable Life Support System Lightens Crew Load," Space/Aeronautics, December 1969.
- (33) Armstrong, R. C., "Life Support System for Space Flights of Extended Time Periods", NASA CR-614, November, 1966.
- (34) Ingelfinger, A. L., and Secord, T. C., "Life Support for Large Space Stations", AIAA Paper No. 68-1032 presented at 5th Annual Meeting, Philadelphia, Pa., Oct. 21-24, 1968.
- (35) Hypes, W. D., "Life Support Systems Integration" paper at the Conference on Bioastronautics at Virginia Polytechnic Institute, Blacksburg, Virginia, August 14-18, 1967.
- (36) NASA CR-73159, "Study of Life Support Systems for Space Missions Exceeding One Year in Duration, Phase IA-Volume II; Mission Studies: prepared by Lockheed Missiles and Space Co., Sunnyvale, Calif. under contract NAS2-3818, 15 Dec. 1967
- (37) Byke, R. M., Kennedy, T. D. and Starns, E. C., "Report on the Development of the Manned Orbital Research Laboratory (MORL) System Utilization Potential, Task Area IV, MORL System Improvement Study" Report SM-48816, Dec. 1965 prepared by Douglas Missiles and Space Division under contract NAS1-3612.
- (38) MOONLAB, "A Study of the Stanford-Ames Summer Faculty Workshop in Engineering Systems Design", edited by La Patra, J. W., and Wilson, R. E., June 24-Sept. 6, 1968
- (39) Bonura, M. S. et al "60-day Manned Test of a Regenerative Life Support System with Oxygen and Water Recovery - Part I: Engineering Test Results" NASA CR-98500, Dec. 1968.
- (40) O'Reilly, W. J., "Project Gemini Extravehicular Life Support System ELSS", NASA CR-92066, Feb. 1967.
- (41) Erlanson, E. P., "Auxiliary Power Systems for a Lunar Roving Vehicle," NASA CR-784, August 1967.
- (42) Reid, R. C., and Richardson, D. L., "Portable Life Support Systems for Extravehicular Activities"; paper presented at the Symposium on Aerospace Life Support Systems, Part I 61st Annual AICHE Meeting, Los Angeles, Calif. Dec. 1-5, 1968.

References (Cont'd)

- (43) Beggs, J. C. "Design and Development of the Apollo Extravehicular Mobility Unit," Hamilton Standard Division, United Aircraft Corp., Windsor Locks, Conn. Report TP-65-01, 1965.
- (44) Briscoe, F. J., "Gas Sensors For Aerospace", Aerospace Life Support-Chemical Engineering Symposium Series No. 63, Vol. 62, PP 63-69, 1966.
- (45) Colombo, G. V., Mills, E. S., "Regenerative Separation of Carbon Dioxide via Metallic Oxides", Chemical Engineering Progress Symposium Series, No. 63, Vol. 62, pp 89-94, 1966.
- (46) Stoll, O. T. and A. L. Brouillet, "Space Shuttle Orbiter Environmental Control and Life Support Systems", Space Division of North American Rockwell and Hamilton Standard Division of United Aircraft, Brochure dated 1971.
- (47) NASA CR-1458, "Trade-Off Study and Conceptual Designs of Regenerative Advanced Integrated Life Support Systems (AILSS)", Hamilton-Standard Division of United Aircraft, January 1970.
- (48) Auerbach, E., and S. Russell, "New Approaches to Contaminant Control in Spacecraft", American Chemical Society Symposium, Atlantic City, N. J., Sept. 1965.
- (49) Huber, D., and T. Jackson, "An Introduction to Trace Contaminant Control Problems", Aerospace Life Support Chemical Engineering Symposium, No. 63, Vol. 62, pp. 55-62, 1966.
- (50) Hanna, G. F., et al, "A Chemical Method for Odor Control", Roy C. Ingersoll Research Center, Borg-Warner Corp., Des Plaines, Illinois, Presented at the New York Academy of Sciences Symposium on Recent Advances in Odor Theory and Control, 1964.
- (51) "-7 PLSS Critical Design Review", Hamilton Standard Division, United Aircraft Corporation, May 1970.
- (52) Tufte, R. J., "Wide Heat Load Range Space Radiator Development", to be presented at the Intersociety Conference on Environmental Control and Life Support (SAE, ASME, AIAA), July 1971.