N72-27114

PRECEDING PAGE BLANK NOT FILMED

8 REGENERABLE THERMAL CONTROL AND CARBON DIOXIDE CONTROL TECHNIQUES FOR USE IN ADVANCED EXTRAVEHICULAR PROTECTIVE SYSTEMS

J. L. Williams, R. J. Copeland, and B. W. Webbon
Vought Missiles and Space Company
Dallas, Texas

INTRODUCTION

Realization of man's full potential for working in space during the ambitious programs of space exploration and research planned for the 1980s and beyond will require considerable extravehicular activity (EVA); longer EVA durations, and considerably more cumulative EVA hours per mission than on any mission to date. If the necessary EVA life support functions were performed using expendables, as is currently done in the Apollo portable life support system (PLSS), the materiel requirements at the vehicle/shelter would be prohibitive.

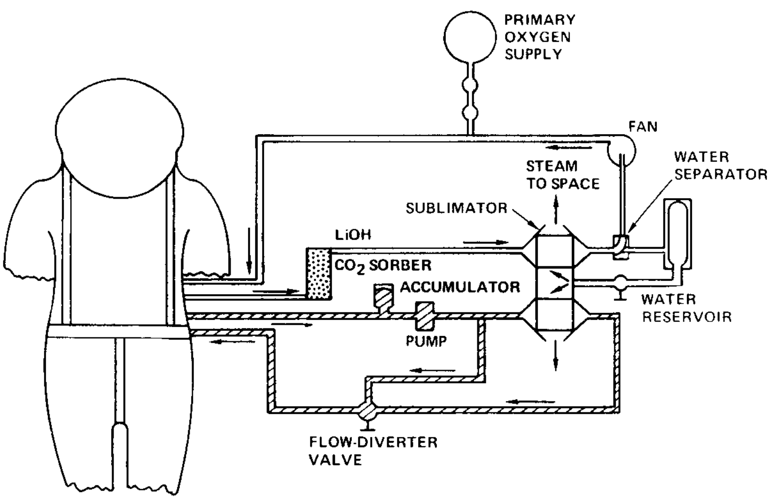


Figure 8.1 *Expendable PLSS-type system.*

Figure 8.1 shows an example of an expendable EVA life support system similar to the PLSS. The atmosphere makeup supply is oxygen stored as a gas in a relatively low pressure (1000 psia) bottle. Carbon dioxide (CO_2) is removed from the ventilation gas in a lithium hydroxide (LiOH) bed. Thermal control is achieved through use of a well-insulated suit, which limits the heat loss from the crewman and his support equipment to a value less than the crewman's metabolic load so that cooling is always required. This cooling is provided by vaporizing water, which is vented overboard, in a sublimator. The liquid-cooled garment (LCG) coolant and the ventilation gas are circulated past the crewman to pick up metabolic heat, through the sublimator for cooling, and then back to the suit.

The PLSS was originally designed for a 4-hr sortie; if the system were enlarged to provide an 8-hr sortie, then approximately 24 lb_m of expendables per man would be required for each EVA. Figure 8.2 shows the expendables breakdown for this case; note that the water expended in the sublimator to provide thermal control represents the bulk of the expendable weight. Carbon dioxide control in the form of LiOH requires approximately one fourth the weight of the water expended for thermal control. Oxygen, which is lost by leakage and in the form of CO_2, makes up about 10 percent of the total expendable weight. Figure 8.2 demonstrates that a closed thermal control system could reduce

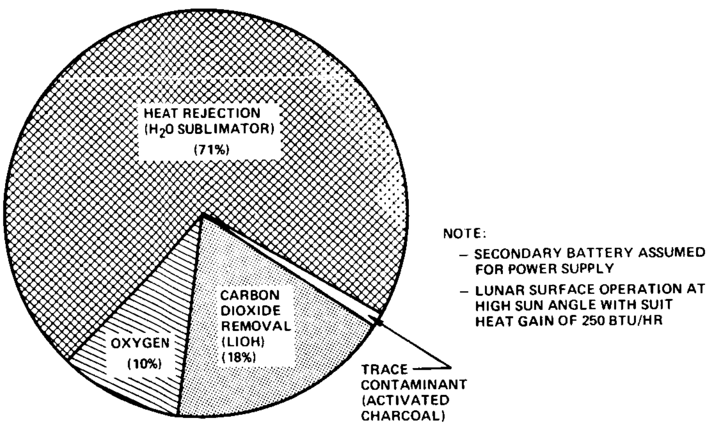


Figure 8.2 *Expendable breakdown for a PLSS-type system on an 8-hour mission.*

the expendables required per 8-hr sortie from 24 lb_m to about 30 percent of that, or 7 lb_m, and if it were coupled with a regenerable CO_2 control system from which oxygen can be recovered, then less than 1 lb_m of expendables would be required per 8-hr sortie.

An expendable EVA life support system such as PLSS is well suited for an Apollo-type mission, since only a few hours of EVA are planned for each mission, and the weight increase for the equipment required for regenerable life support would more than offset the savings in expendable weight. However, as the number of EVAs per mission is increased, the crossover point at which the weight of the expendables exceeds the weight of the regeneration equipment is quickly reached. Beyond this point, a regenerable system provides dramatic weight and volume savings for the vehicle/shelter.

This paper summarizes the work performed in a study of advanced extravehicular protective systems (AEPS) that might be used for extended EVA in earth orbit, on the lunar surface, or on Mars. The study was performed by Vought Missiles and Space Company (VMSC) of LTV Aerospace Corporation for the Biotechnology Division of NASA - Ames Research Center under contract NAS 2-6022.

OBJECTIVES

The primary objective of the AEPS study was to identify and define the most promising regenerable life support techniques and concepts that might be applied to a portable EVA life support system. Other objectives were to determine the tradeoff points between expendable, partially regenerable, and fully regenerable systems, and to generate the data necessary to define the weight and volume envelope required to support a given number of EVAs using the AEPS equipment.

Candidate life support subsystem concepts were separated into the following functional categories.

1. Expendable
2. Partially regenerable
   (a) Regenerated during the EVA
   (b) Regenerated at the base between EVAs
3. Fully regenerable
   (a) Regenerated during the EVA
   (b) Regenerated at the base between EVAs

The primary emphasis in this study was on fully regenerable systems. However, the most promising candidates in the other categories were also identified and characterized to determine the required tradeoff points.

AEPS SPECIFICATIONS, GUIDELINES, AND CONSTRAINTS

The specifications for the AEPS (ref. 1) are given in table 8.1. These specifications are generally intended to ensure the safety of the crewman and to maximize his mobility and work performance. The specifications most critical to the definition of the AEPS are the EVA duration and frequency (one 8-hr sortie per day), the allowable suit inlet CO_2 partial pressure (4 mm HgA nominal with 7.5 mm HgA maximum), and the metabolic rate (1600 Btu/hr average per sortie with a peak of 3500 Btu/hr and a mission average of 1200 Btu/EVA hour).

Table 8.1 *AEPS specifications.*

EVA DURATION (AT AVERAGE METABOLIC RATE)	8 + HOURS
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.
SUIT GAS COMPOSITION	3.7 – 7.5 PSIA PURE OXYGEN
HUMIDITY CONTROL a. NOMINAL SUIT INLET DEW POINT b. MAXIMAL SUIT INLET DEW POINT	 45°F 60°F
VENTILATION (MINIMAL) a. INLET FLOW RATE b. INLET GAS TEMPERATURE c. SUIT LEAKAGE	 9 ACFM 50 – 70°F 180 SCCM
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
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
LIQUID TRANSPORT LOOP FLOW	4 LB/MIN.
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
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

The guidelines and constraints (ref. 1) shown in table 8.2 establish other criteria for defining and comparing different candidate AEPS and subsystems. The penalty factors for power and thermal energy are not conservative, but they should be well within the state-of-the-art in the AEPS operational time frame. These penalty factors were found to have a profound influence on the total weight of some regenerable systems, since large quantities of energy may be required for regeneration. Liberal EVA system weight and volume limits were deliberately selected to present as wide a range of candidate subsystem concepts for evaluation as possible.

Table 8.2 *Guidelines and constraints.*

BASE PENALTY FACTORS	
POWER	500 LB/KW_e
THERMAL ENERGY (HEATING OR COOLING)	100 LB/KW_t

ALLOWABLE AEPS WEIGHT AND VOLUME (DESIGN GOALS)

TRANSPORTER	WT. (LB)	VOL. (IN^3)
BACKPACK AND CHESTPACK	200	8,600
"MET" TYPE TRANSPORTER	200	8,600
POWERED VEHICLE	1000	40,000

DESIGN ENVIRONMENTS

As previously stated, the AEPS study was to consider EVA systems for missions in earth orbit, on the lunar surface, and on Mars. Table 8.3 summarizes the results of a brief investigation into the EVA environmental conditions that would be encountered on each of these missions.

Table 8.3 *AEPS design environments.*

	SOLAR FLUX (B/HR FT2)	ALBEDO	EQUIV. SURFACE TEMP. RANGE (°R)	MEAN GRAV. CONSTANT (g)	ROTATIONAL PERIOD (HRS)	ATMOS. PRESSURE (MB)
EARTH ORBIT	442	0.35	453	–	–	–
LUNAR SURFACE	442	0.07	170 – 760	0.17	655	–
MARS SURFACE	164 TO 240	0.17	POLE: 140 – 470 EQUATOR: 310 – 590	0.38	24.61	APPROX. 6 (0.088 PSIA)

The primary influence of the external environment on the AEPS is a heat leak either into or out of the AEPS control volume. The lunar surface is particularly severe in this respect since the long lunar day and the large solar flux cause the surface material to reach temperatures of more than 300° F (at the bottom of some craters). The lunar night is at the other extreme since the surface temperature may drop to - 290° F. These extremes of thermal environment cause a heat leak through an Apollo suit ranging from about -300 to +350 Btu/hr and this can have a significant impact on the total AEPS heat load.

Another important factor is the lack of gravitational body force in earth orbit. This must be considered in determining the feasibility of actually constructing the hardware required to perform the life support functions.

The influence of all of the factors shown in table 8.3 was considered in the selection of life support concepts for the different missions. However, a different philosophy was assumed than was used for the selection of the Apollo PLSS. The PLSS was required to be operable both in earth orbit and on the lunar surface. As shown, the EVA conditions for these cases are significantly different, necessitating system compromises that would not be required if the system were optimized for a particular mission. This approach was necessary for the Apollo application, but for more advanced AEPS missions, requiring considerable EVA, there would be an advantage to tailoring the EVA systems for specific conditions.

LIFE SUPPORT SUBSYSTEM CANDIDATES

The generalized life support subsystems required in an AEPS are shown in figure 8.3. It was previously shown that the heat rejection and CO_2 control subsystems contribute about 90 percent of the expendable mass used in present-day systems. Therefore, these areas were given prime consideration. Other areas, such as atmosphere supply and power supply, were also investigated to determine if any significant improvements might be expected, and particularly to identify any subsystem concepts that might perform more than one life support function–for example, combined atmosphere supply and CO_2 control.

Atmosphere Supply Systems

The AEPS specifications (table 8.1) call for a pure oxygen atmosphere at 3.7 to 7.5 psia, and oxygen-nitrogen atmosphere at 10 to 14.7 psia for the primary vehicle/shelter. An evaluation of this difference in atmospheric pressure and composition indicated that it is not advisable for a crewman to transfer directly between these two atmospheres without some transition period. The primary problem is the possibility of aeroembolism (the bends) caused by a sudden reduction in

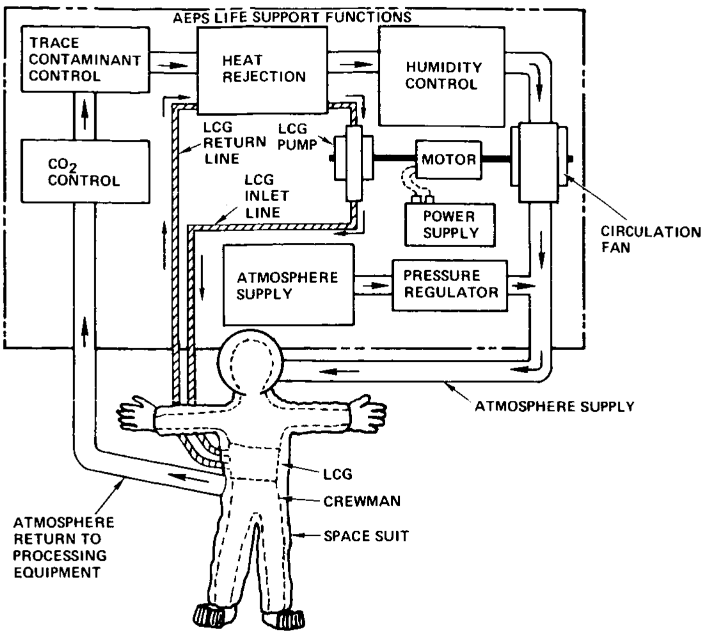


Figure 8.3 *AEPS life support system.*

the total pressure of the breathing gas. Avoidance of this problem requires either the adoption of a higher pressure, two-gas suit, or provision of equipment and time to reduce the nitrogen dissolved in the crewman's bloodstream to a safe level prior to the EVA. The first approach was found to be undesirable because of probable limitations in suit mobility associated with high suit pressure and the danger of crippling bends if the suit pressure was suddenly dropped—for example, as a result of suit puncture. Therefore, brief consideration was given to determining the techniques and types of equipment required to remove the nitrogen from the crewman's bloodstream prior to the EVA. For some missions the inclusion of the preconditioning equipment might be prohibitive, so a reliable, mobile, high-pressure two-gas suit might be required. A more detailed study of this problem [than was intended in the AEPS program] is required to determine the optimum suit gas composition and pressure and to more precisely identify the interfaces between the EVA and the base atmosphere systems.

Based on this preliminary investigation, a 5 psia, pure oxygen atmosphere was selected for the AEPS study in accord with the state of suit technology and the interests of system simplicity. The primary oxygen supply system is required to maintain this pressure by supplying gas at the proper pressure and flow rate to make up for normal suit leakage and the oxygen consumed by the man and removed by the CO_2 control system. It was assumed that an emergency system would be available to maintain suit pressure if required.

The candidate oxygen supply concepts that were considered are summarized in table 8.4, which shows that oxygen may be stored as a pure substance in various states or chemically combined in various ways. The chemical storage methods, such as chlorate candles and superoxides, and combined O_2 supply/CO_2 removal systems, were all found to have the problem of accurately controlling the rate of oxygen production to match the AEPS requirement of rapidly varying metabolic load in a small, closed volume. This problem may be overcome by using accumulators and other devices, but the addition of this equipment leads to excessive weight for an EVA system. There also is a problem in regenerating many of these chemicals to produce a closed system. Other systems, such as water electrolysis, and Bosch and Sabatier reactors, may be profitably applied at the primary base, but were found to be too large for EVA use.

It was concluded that high-pressure (approximately 5,000 psia) gaseous oxygen storage is the optimum method for AEPS. This system combines low weight and volume with maximum reliability and ease of integration with base systems. The only base regeneration requirement is a compressor to fill the EVA tank; the power required for this compressor is significantly less than that required for any other system. The construction of a 5,000-psia tank and pressure regulator

Table 8.4 *Candidate CO_2 supply systems.*

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

is well within present technology. Further improvements to permit the use of higher pressures also may reduce the tank weight and volume. Therefore, it is recommended that a high-pressure oxygen supply be used for EVA systems for the foreseeable future.

Power Supply, Trace Contaminant Control, Humidity Control

It was found that the expendable weight and EVA equipment weight were so small that no significant total weight reduction would be realized by developing new concepts in the areas of power supply and control of trace contaminants and humidity. All AEPS were assumed to use rechargeable lithium halide batteries for power supply with expendable activated charcoal and biological filters for trace contaminant control. The humidity control system depends on the temperature level available from the heat rejection system. Simple condensation and separation were assumed for systems with low temperature heat rejection (below 45° F), and a silica-gel desiccant for systems with higher heat rejection temperatures (from 45° to 70° F). The weight and volume of all of these subsystems and the power supply recharge equipment were included in the AEPS total integrated system analysis.

Carbon Dioxide Control Systems

A comprehensive survey of the pertinent literature was made to identify previously investigated techniques for controlling the CO_2 level in a closed volume and to define new concepts that appear promising from a theoretical standpoint.

The most promising techniques identified are shown in table 8.5, and all are considered feasible for use in an AEPS. The concepts were screened in terms of system size, expendable requirements, power requirements, and similar factors; as shown in the table, many were discarded at this stage because of obvious problems with excess size, prohibitive regeneration penalties, or because they did not offer any potential improvement over existing systems. Detailed analysis was then performed and a conceptual system design produced for each remaining technique. A final screening process reduced the candidate systems to the following four: LiOH (expendable), solid amine (partially regenerable), $MgOH_2$ (regenerable at base), and KOH (regenerable at base).

Lithium hydroxide reacts readily with carbon dioxide, and the LiOH system, although fully expendable, is the lightest weight and most compact CO_2 control system available. Lithium hydroxide is thus very satisfactory for missions where a relatively small number of EVAs are required and for EVA sorties requiring maximum mobility. No other expendable CO_2 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 (Li_2CO_3)

Table 8.5 *Candidate* CO_2 *control methods.*

METHOD	DETAILED ANALYSIS	PRELIMINARY ANALYSIS ONLY	COMMENTS
CHEMICAL EXPENDABLE			
• LiOH	X		GOOD FOR LIMITED NUMBER OF SORTIES
• KO_2, NaO_2		X	NO ADVANTAGE OVER LiOH
• Li_2O_2		X	NO ADVANTAGE OVER LiOH
CHEMICAL, REGENERABLE			
• LiOH	X		HIGH REGENERATION PENALTY
• KOH	X		MODERATE POWER FOR BASE REGENERATION
• KO_2, NaO_2, Li_2O_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
ADSORPTION			
• 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
ABSORPTION			
• 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 a. LIQUID LOOPS b. MEMBRANES		X	EXCESSIVE WATER LOSS
• DEAD END WATER SOLUTION OF CARBONATES		X	EXCESSIVE EVA SIZE
VACUUM VENT			
• 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
OTHER			
• 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

produced during the EVA. However, considerable amounts of power are required because Li_2CO_3 is relatively insoluble in water, making simple electrolysis impractical. Thermal regeneration is not feasible either. Therefore, LiOH was judged to be impractical for use in the nonexpendable mode.

Solid amine systems are being researched for use as CO_2 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: one bed absorbs CO_2 from the gas stream while the other bed is desorbed to space. The system is classed as partially expendable because the CO_2 sorbent is reused, but the CO_2, the water vapor, and oxygen contained in the bed free volume are vented to space. Solid amine CO_2 sorbents have a low capacity for CO_2 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 CO_2 absorption capacity of the bed depends critically 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 CO_2 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.

The literature survey provided evidence of some preliminary investigations into the use of other alkaline-earth hydroxides other than LiOH as a CO_2 sorbent. All these materials are very basic and the reaction with the acid gas, CO_2, is an acid-base neutralization reaction, with the resulting formation of a carbonate salt and water. These hydroxides all have fairly high CO_2 capacity so that the bed size is comparatively small. Lithium hydroxide is preferred when the application requires an expendable sorbent because of its low molecular weight. However, as previously stated, the chemical properties of 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 so that thermal regeneration is possible and the relatively high solubility of potassium carbonate 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 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 MgO, which can then by hydrated to $Mg(OH)_2$ by circulating wet steam through the bed.

A workable system concept is shown in figure 8.4. The $Mg(OH)_2$ 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.

The feasibility of this concept has been demonstrated (ref. 2). However, the lifetime of $Mg(OH)_2$ pellets after repeated cycling has not been investigated. Data are needed to determine whether the pellets need to be reformed after each regeneration cycle and to define the

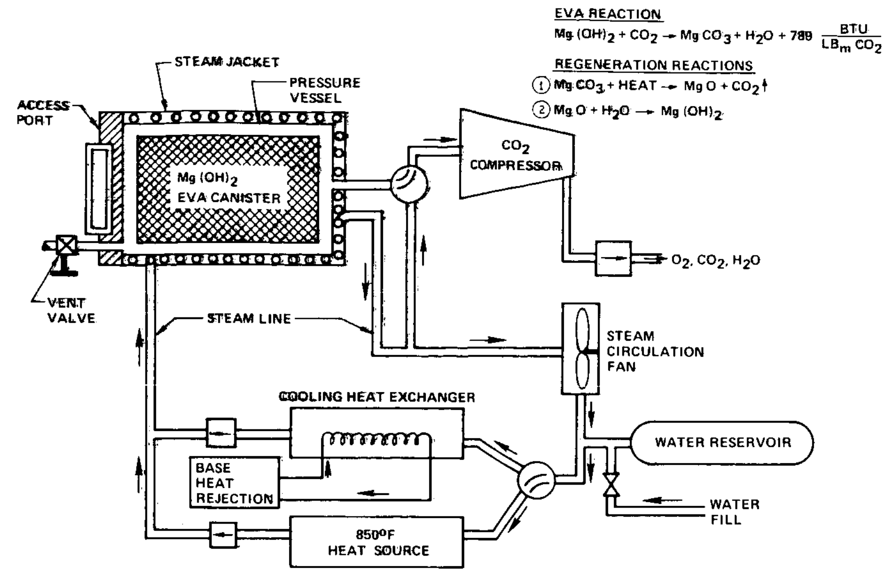


Figure 8.4 $Mg(OH)_2$ *regeneration facility.*

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 depends critically on the penalties assumed in table 8.2.

The EVA operation of the CO_2 sorber system is identical to that of the LiOH system, except that a larger canister is required. The 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 8.5 shows a unique design, conceived by VMSC, that uses a circulating liquid solution of KOH rather than a solid particle bed. The advantage of this concept is that it overcomes one of the fundamental limitations on the efficient use of a solid sorbent bed—that 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 to maximize the surface area exposed to the gas stream. These pellets tend to cake during the EVA due to trapping of the product water. This increases the pressure drop and further complicates regeneration since the pellets must be reformed.

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 in the precipitation of K_2CO_3. The concentration of K_2CO_3 in the

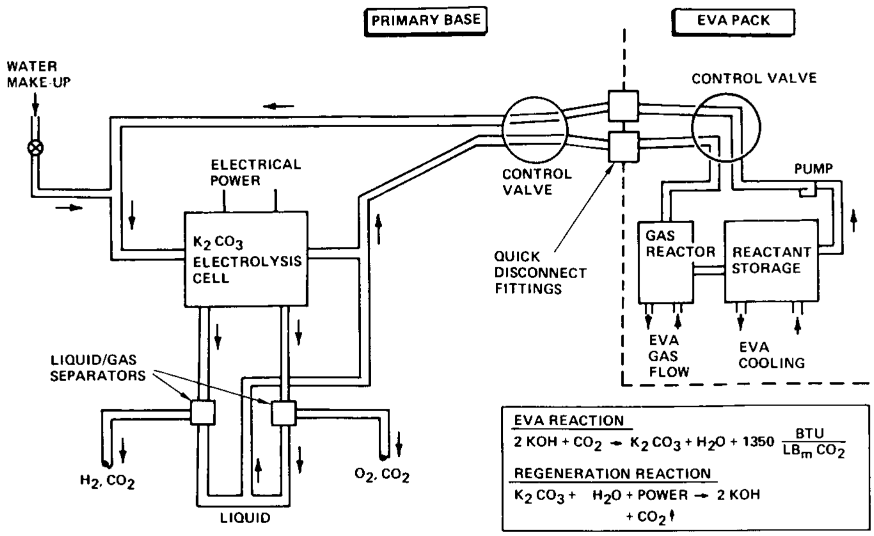


Figure 8.5 *Liquid* KOH/CO_2 *sorbent regeneration facility.*

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 for any other regenerable system. However, considerable development is needed to provide an efficient and reliable EVA system.

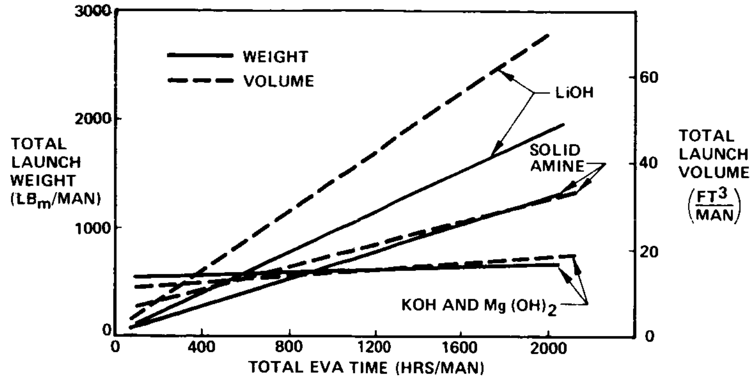
Base regeneration (fig. 8.5) is accomplished by redissolving the precipitated carbonate and electrolysis of the resulting solution. The CO_2 is removed in the electrolysis cell, and the result is a concentrated solution of KOH ready for EVA use.

In a primitive experiment, VMSC demonstrated the feasibility of this system. 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 (ref. 3). Therefore, a partial credit can be taken for the oxygen produced by this method.

The projected total system size for the KOH system, including all penalties, is comparable to the $Mg(OH)_2$ system previously discussed, and for 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 further investigation.

Figure 8.6 shows the total launch weight and volume as a function of EVA time for the most promising CO_2 control subsystems. The curves show that expendable LiOH is the smallest subsystem for less than about 50 hr EVA. Between 50 and 900 hr EVA the solid amine subsystem has the lowest total subsystem weight; it also 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 hr EVA, but at the penalty of increasing the EVA weight. This sacrifice is believed to be worthwhile since at 1600 hr EVA, the $Mg(OH)_2$ system saves more than 1000

lb_m over LiOH. The data presented in figure 8.6 were used in preparing similar curves for total AEPS.



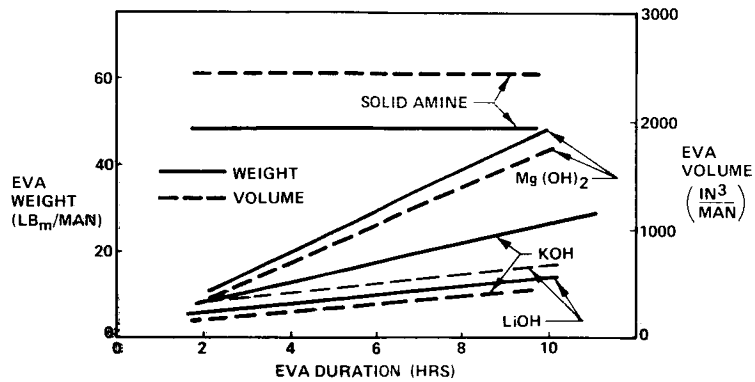


Figure 8.6 *AEPS CO_2 control system size comparison.*

Thermal Control Systems

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. However, the low heat exchanger effectiveness of the current LCG requires an inlet temperature of about 40° F to remove the maximum metabolic load (3500 Btu/hr); the outlet temperature is only 55° F. This low temperature close to 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 incorporated where appropriate.

Table 8.6 gives the methods of rejecting heat from an AEPS that were considered in this study. Several of the heat rejection mechanisms, such as conducting heat sinks, have specific applications, while others, such as evaporation, are more general.

Table 8.6 *Means for accomplishing heat removal from AEPS.*

MECHANISM	MASS & HEAT TRANSFER			PHASE CHANGE				
	CONDUCTION	CONVECTION	RADIATION	EVAPORATION	FUSION	CRYSTALLINE STRUCTURE CHANGE	WORK	CHEMICAL REACTION
GOVERNING EQUATION	$q_L = \frac{KA}{X}(T_L - T_S)$	$q_L = hA\ (T_L - T_S)$	$q_L = \sigma\epsilon A\ (T_L^4 - T_S^4)$	$q_L = \dot{m}\lambda$	$q_L = m\lambda$	$q_L = m\lambda$	$q_L = w\ (\frac{T_L}{T_S - T_L})$	$q_L = m\Delta h_o$
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	NONE	NONE	SMALL	LARGE	NONE	NONE	SMALL	NONE

NOTE: T_S = SINK TEMPERATURE
T_L = SYSTEM HEAT REJECTION TEMPERATURE 40°F

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"

The limiting factors shown in the table are the fundamental physical factors that influence the system design. Systems such as a space radiator must be sized to reject the maximum expected rate of heat production. The capacity of the system (average rate multiplied by EVA duration) is a factor only in that the system battery must have the required capacity; thus, this type of system is said to be rate limited. The phase change concepts are said to be capacity limited because a fixed quantity of heat sink material is carried and all cooling capacity is lost when this material is expended. The rate at which the material is expended has little impact on system size and weight.

By means of a preliminary screening technique involving detailed analysis and preliminary sizing, the candidate concepts were reduced to four systems meriting consideration at the total system level: water evaporator (expendable), radiator (supplemented by expendables), refrigerator (supplemented by expendables), and astronaut heat sink (AHS) (fully regenerable).

No heat rejection subsystem having an 8-hr operating capacity without expendables was small enough to be integrated entirely into a backpack system. Thus, some type of separate support system is required, which could be mounted on a MET-type transporter or installed on a powered vehicle.

There are two functionally different methods of supporting the AEPS backpack from a separate system; the two systems can be connected by an umbilical, or the support system can hold cooling modules for manual installation 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 percent of the EVA duration. Therefore, the radiator and refrigerator systems, which have the capability to operate as completely closed systems, nevertheless are considered to be supplemented by expendables, since expendables may be used during the nonumbilical portion of the EVA.

The water evaporation system is assumed to be a sublimator similar to that used in the Apollo PLSS with an enlarged water tank to increase the system capacity to 8 hr. This system would have a pack weight of about 40 lb_m and would expend approximately 17 lb_m of water during an 8-hr EVA. The sublimator is a compact and reliable heat rejection device, but its large expendable requirement makes it prohibitively heavy for missions requiring more than about five EVA per man.

The simple radiator and the refrigeration systems are rate limited, and they would be prohibitively large when designed to reject the maximum expected 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 the total system heat load, including equipment cooling and a nominal environmental heat leak, is about 2000 Btu/hr for an average metabolic load of 1600 Btu/hr. Therefore, this value was taken as the baseline 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 has several limitations. The radiating temperature is limited to the temperature available from the LCG and will therefore be less than about 70° F; heat rejection from the radiator is thereby limited to a maximum of 140 Btu/hr ft^2 so that the minimum possible radiator area is about 14 ft^2 for 2000 Btu/hr. The actual area will be considerably greater because of limitations imposed by radiator fin effectiveness, surface optical properties, and the influence of the thermal environment. 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 because of 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. On the basis of conservative estimates for motor and compressor efficiency, it was found that a COP of 2.9 could be achieved with an evaporator temperature of 40° F and a condenser temperature of 130° F. 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-ft 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, to be discussed later, is also included in the backpack, bringing the total heat rejection system weight to about 95 lb_m. This system would provide cooling for nonumbilical 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 approach to a closed AEPS heat rejection system is illustrated in figure 8.7. This concept has been designated the astronaut heat sink (AHS). The basic concept is extremely simple. An aluminum pack containing 15 lb_m of ice is mechanically clamped between two heat exchanger modules. Heat is rejected by melting the ice. Since the heat of fusion of ice is only about 15 percent of the heat of sublimation, approximately 75 lb_m of ice are required for a nominal EVA (1600 Btu/hr metabolic load). This is too large a subsystem mass 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.

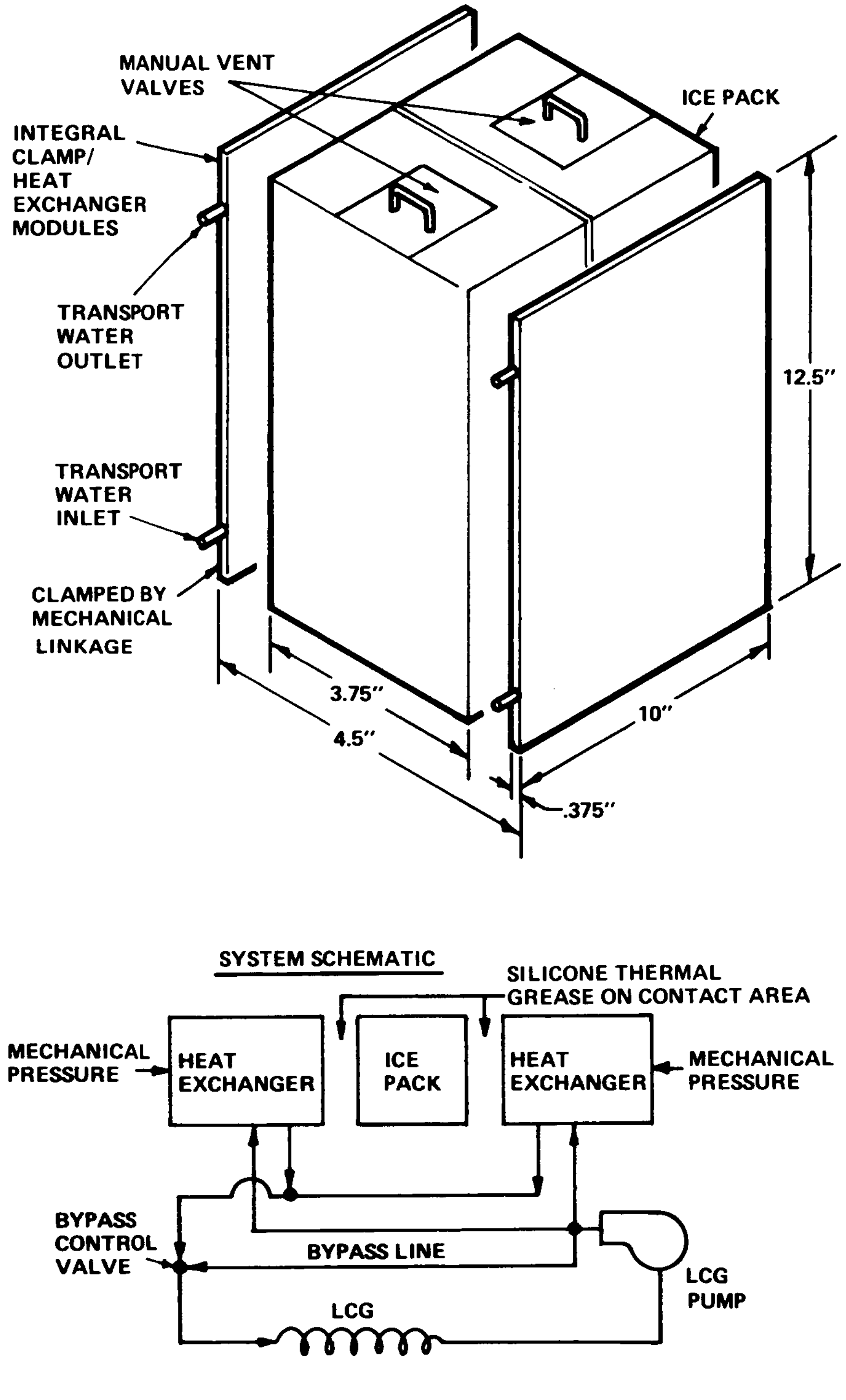


Figure 8.7 *Closed AEPS heat rejection system.*

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

An investigation of other phase change materials in addition to water was made as part of the study. It was concluded that water is superior to any other substance since it has a high heat capacity in a temperature range that is suitable for the AEPS system, it is completely nontoxic in all forms, and it is readily available at the base without providing special equipment.

A unique feature of the AHS containing water is the contingency mode of operation. 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 lb_m of water can then be expended by controlled evaporation. This extends the capability of the AHS system to allow a complete 8-hr EVA without the support modules but with a penalty in water expended. This contingency mode adds considerable flexibility to the AHS concept.

A fusible type heat sink is assumed to be integrated into the backpack for use as the top-off system required for the refrigeration system. This allows 1 to 2 hr of nonumbilical operation without expending any water; operation in the expendable mode affords an additional 5 to 6 hr.

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.

The modular and umbilical approaches to AEPS thermal control are illustrated in figure 8.8. 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.

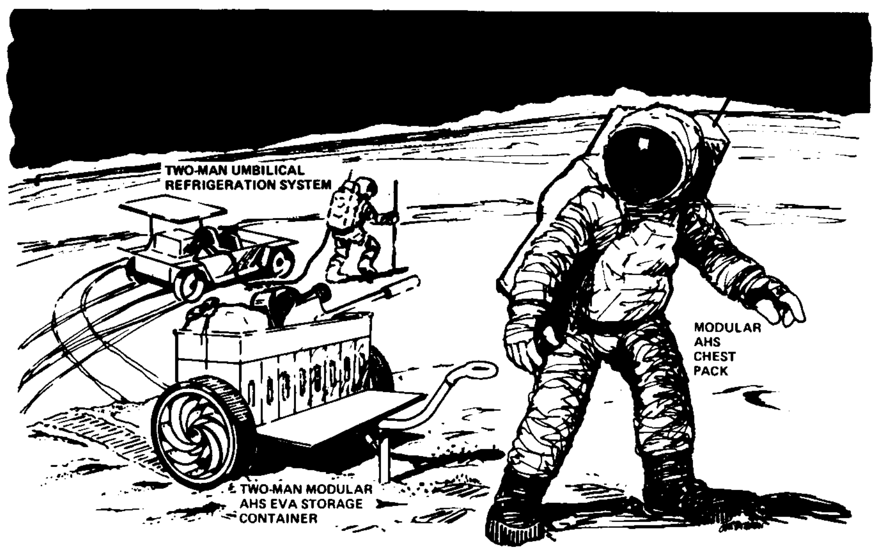


Figure 8.8 *Modular and umbilical approaches to AEPS thermal control.*

The weights and volumes of these promising systems are shown in figure 8.9. The figure shows that the expendable weight of the sublimator imposes an extremely large penalty for any mission requiring numerous EVAs. The weight and volume of the AHS/refrigerator system increases with the number of EVA hours, because of the assumption that 30 percent 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 percent of the time, no water would be expended on a nominal

EVA and the AHS/refrigerator would become the lightest weight thermal control system. For the simple AHS system, it was assumed that the expendable mode would be used only during emergencies, and therefore no expendable penalty was assigned to this system. Figure 8.9, 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 system does.

AEPS TOTAL SYSTEM CONCEPTS

The most promising total system concepts identified by the AEPS study are summarized in table 8.7. The first system, which uses LiOH and a sublimator for CO_2 control and thermal control, respectively, is similar to the PLSS except that it has been enlarged to accommodate an 8-hr EVA sortie and it is assumed to have long-term reuse capability. System 2 retains the LiOH for CO_2 control but uses an AHS heat rejection system; thus the expendables are reduced to about 7 lb_m per EVA. System 3 utilizes a solid amine CO_2 control subsystem with an AHS/refrigerator for thermal control. Systems 4 and 5 offer closed CO_2 control and closed heat rejection.

The total launch weight and volume of these systems as a function of cumulative EVA time are shown in figure 8.10. An expendable system is the lightest for less than about 50-hr of EVA because it does not require base regeneration equipment as the closed systems do. The LiOH/AHS

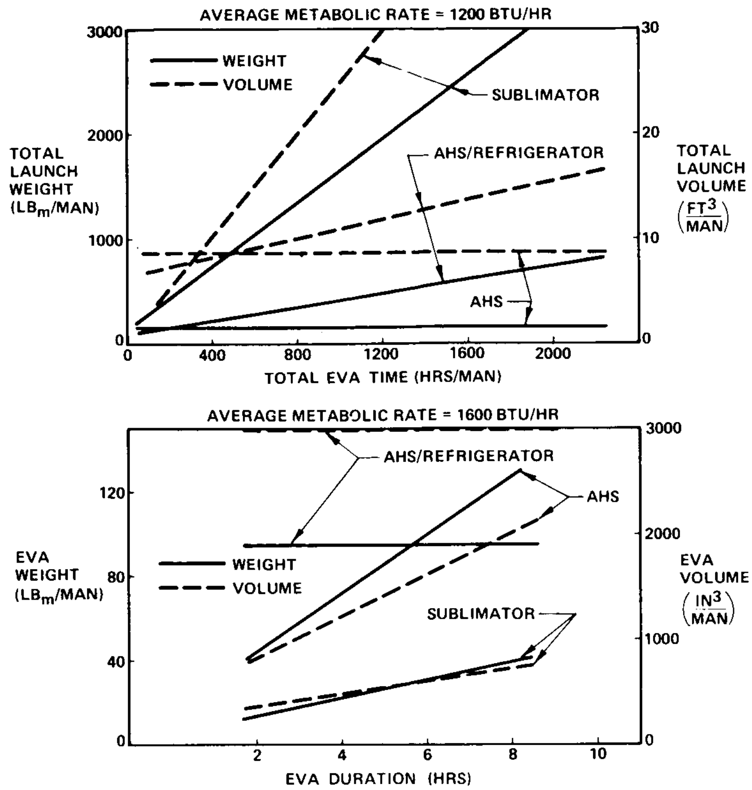


Figure 8.9 *AEPS thermal control system size comparison.*

Table 8.7 *Integrated AEPS systems.*

SYSTEM	CO_2 CONTROL	THERMAL CONTROL
1	LiOH	SUBLIMATOR
2	LiOH	AHS
3	SOLID AMINE	AHS/REFRIGERATOR
4	Mg $(OH)_2$	AHS
5	Mg $(OH)_2$	AHS/REFRIGERATOR

ALL SYSTEMS INCLUDE

- O_2 SUPPLY – HIGH PRESSURE GAS
- POWER SUPPLY – LITHIUM-HALIDE SECONDARY BATTERY
- TRACE CONTAMINANT – ACTIVATED CHARCOAL CONTROL

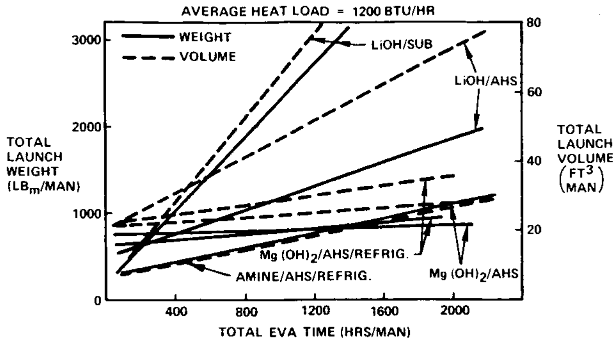


Figure 8.10 *Total launch weight and volume.*

system is shown to be noncompetitive with the closed systems on a total weight basis, regardless of the number of EVA hours. However, this system does offer a considerable weight saving when compared with a fully expendable system, and it would therefore seem to be a logical extension of present capabilities when a moderate number of EVAs are planned.

System 3 is shown to have the lowest total system weight from about 50 to 1300 hr EVA. The pack weight and volume of this system are extremely large and this, along with the inherent reliability problems associated with the cyclic solid amine system, makes this the least desirable of the AEPS total system concepts. The weight and volume savings possible by utilizing closed EVA life support systems for missions requiring more than about 1300 hr EVA is clearly indicated on figure 8.10. This figure can be used both to estimate the weight and volume required for a given number of EVA hours or conversely, to determine the number of EVA hours that can be accomplished within a given weight and volume envelope.

Figure 8.11 shows the influence of EVA duration on the size of the EVA system. Both pack weight and total EVA weight are shown. The pack weight is the actual weight carried per man while the total EVA weight includes the pack and the support system. Figure 8.11 shows that there is no significant weight reduction by reducing the EVA duration to less than 8 hr. The figure also illustrates that a savings in total system weight by reducing expendables can only be accomplished by increasing the EVA weight.

Conceptual system schematics and pack designs for Systems 4 and 5 are shown in figures 8.12 and 8.13, respectively. These designs were produced to demonstrate the feasibility of packaging the candidate regenerable subsystem concepts into a practical pack design. The weight breakdown of the packs is also included.

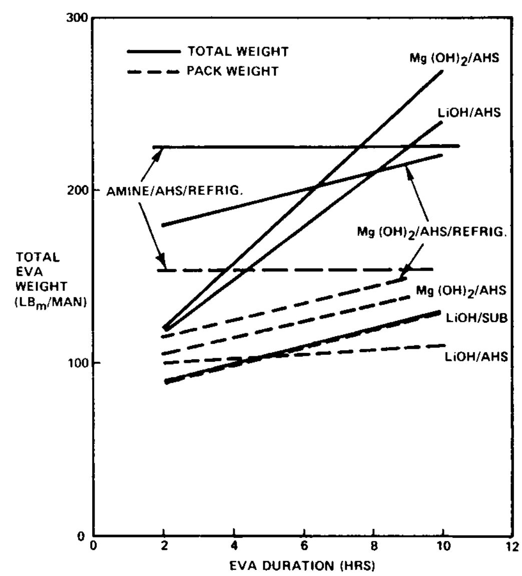
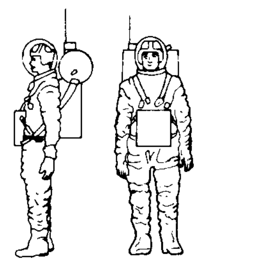


Figure 8.11 *Influence of duration on size of system.*

CONCLUSIONS AND RECOMMENDATIONS

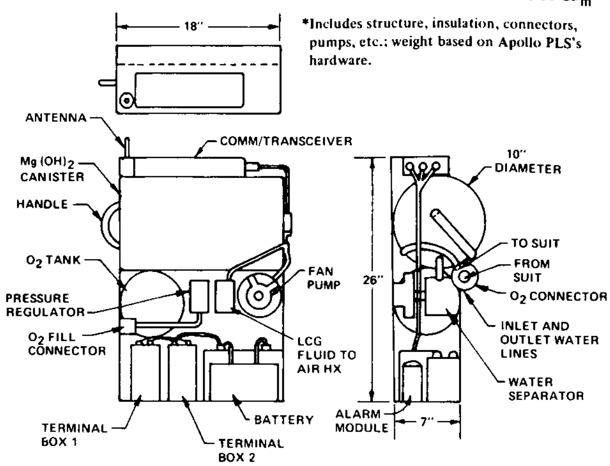
The following conclusions were reached as a result of the AEPS study:

1. Regenerable EVA life support systems are feasible.
2. The most promising approach is to regenerate the EVA systems at the primary base.
3. Regenerable systems offer large total weight savings with an increase in EVA weight.



	WT (LB)
BACKPACK	
OXYGEN BOTTLE	10.40
$Mg(OH)_2$ REACTOR	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

*Includes structure, insulation, connectors, pumps, etc.; weight based on Apollo PLS's hardware.



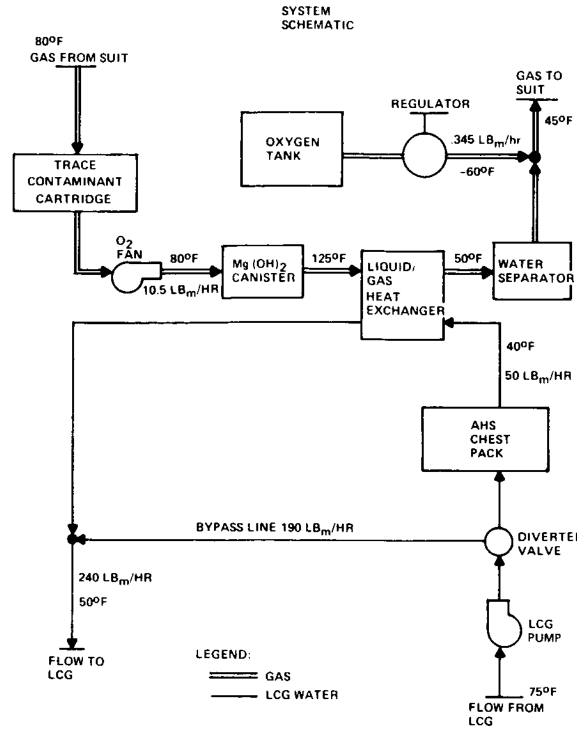
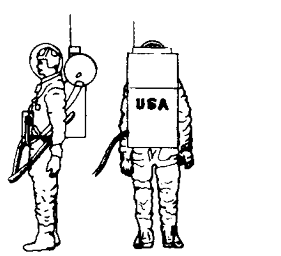
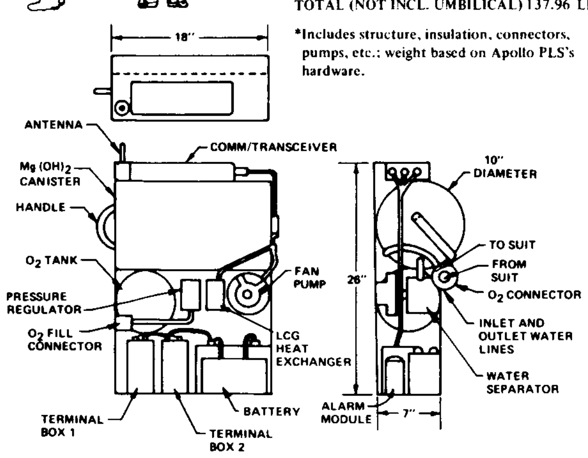


Figure 8.12 *Backpack with* $Mg(OH)_2/CO_2$ *control and chest pack AHS heat rejection system.*



WEIGHT SUMMARY	
BACKPACK	
OXYGEN BOTTLE	10.40
$Mg(OH)_2$ REACTOR	38.90
TRACE CONTAMINANT	0.30
BATTERY	10.50
AHS	30.00
STD & MISC	47.30*
CHEST PACK	
RCU	5.6
TOTAL (NOT INCL. UMBILICAL)	137.96 LB_m

*Includes structure, insulation, connectors, pumps, etc.; weight based on Apollo PLS's hardware.



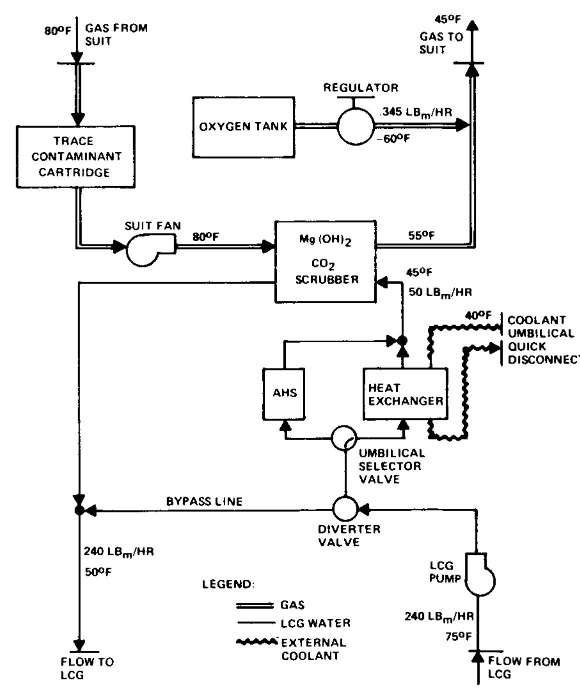


Figure 8.13 *Backpack with* $Mg(OH)_2/CO_2$ *control and AHS/refrigerator heat rejection system.*

Carbon Dioxide Control

The most promising closed CO_2 control concept identified by this study is the solid pellet, $Mg(OH)_2$ system. The liquid KOH system has the potential to have a smaller EVA mass and volume than that of the $Mg(OH)_2$ system, but its feasibility has not been demonstrated and should be investigated further.

Thermal Control

Two promising approaches to closed thermal control were identified. The AHS system uses modular fusible heat sinks, with a contingency evaporative mode, to allow maximum EVA mobility. The AHS/refrigerator top-off subsystem requires an umbilical to minimize expendables, but less EVA time is used to operate the system, since there is no requirement to change modules. Both of these subsystems are thought to be practical solutions to the problem of providing closed heat rejection for an EVA system. The selection of the optimum approach for a particular mission must be made at the detailed mission planning stage.

REFERENCES

1. Anon: Request for Proposal for Advanced Extravehicular Protective System (AEPS). Ames Research Center, RFP A-15999 (AC-30), Feb. 11, 1970.
2. Colombo, G. V.; and Mills, E. S.: Regenerative Separation of Carbon Dioxide via Metallic Oxides, Chemical Engineering Progress Symposium, vol. 62, no. 63, 1966, pp. 89-94.
3. Anon: Preliminary Results from an Operational 90-Day Manned Test of a Regenerative Life Support System. NASA SP-261, 1970.