7-17-2006

Innovative Schematic Concept Analysis for a Space Suit Portable Life Support Subsystem

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Scholarly Commons Citation

Schuller, M., Kobrick, R., Lalk, T., Wiseman, L., Little, F., & et al. (2006). Innovative Schematic Concept Analysis for a Space Suit Portable Life Support Subsystem. , (). https://doi.org/10.4271/2006-01-2201

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SAE TECHNICAL PAPER SERIES

2006-01-2201

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36th International Conference on Environmental Systems (ICES)
Norfolk, Virginia
July 17-20, 2006

SAE International™

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ISSN 0148-7191

Printed in USA

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ABSTRACT

Conceptual designs for a space suit Personal Life Support Subsystem (PLSS) were developed and assessed to determine if upgrading the system using new, emerging, or projected technologies to fulfill basic functions would result in mass, volume, or performance improvements. Technologies were identified to satisfy each of the functions of the PLSS in three environments (zero-g, Lunar, and Martian) and in three time frames (2006, 2010, and 2020). The viability of candidate technologies was evaluated using evaluation criteria such as safety, technology readiness, and reliability. System concepts (schematics) were developed for combinations of time frame and environment by assigning specific technologies to each of four key functions of the PLSS -- oxygen supply, waste removal, thermal control, and power. The PLSS concepts were evaluated using the ExtraVehicular Activity System Sizing Analysis Tool, software created by NASA to analyze integrated system mass, volume, power and thermal loads. The assessment resulted in the Texas Engineering Experiment Station recommending to NASA an evolution path from the existing PLSS to a long duration, low mass PLSS suitable for Martian missions.

INTRODUCTION

Extended human exploration of the lunar and Martian surfaces poses many challenging performance and logistical demands on space suits and associated subsystems, such as the Portable Life Support Subsystem (PLSS). The PLSS currently in use is very similar to the one used in the Apollo program in 1960's and early 1970's. A number of new or improved technologies have matured in the 30 years since Apollo, and with the advent of the Vision for Space Exploration (VSE) it is timely to revisit the overall system concept of the PLSS. The goal of this study was to assess the viability of these new or improved technologies, develop and evaluate PLSS conceptual designs using them, and determine whether these changes resulted in mass, volume, and performance improvements for the overall PLSS.

To begin addressing these design tasks, a team led by the Texas Engineering Experiment Station (TEES) investigated innovative schematic concepts for the suit's PLSS. Over one hundred candidate technologies capable of performing various functions required within the PLSS were initially identified. Each candidate technology was characterized and compiled in an extensive technology database to quantify key information regarding performance, technology readiness, and safety.

Given the large number of technologies available, the time and resource constraints on the study required excluding most of them from the detailed assessment. The rationale for excluding any of the technologies from further consideration was documented for future reference.

Viable technology concepts were grouped into integrated schematics. These schematics were assessed using the ExtraVehicular Activity System Sizing Analysis Tool (EVASSAT), software created by NASA, to analyze mass and volume parameters and to balance power and thermal loads as a check on each integrated system. We used these results to perform both absolute (Does a concept meet the mass and volume requirements?) and relative (How well does a concept meet those requirements?) evaluations of all PLSS concepts developed. The schematics that met the evaluation criteria were assessed in detail to rank the relative merit of the downselected PLSS concepts.

The schematic developed for Apollo and assessed in the Sutton study (Sutton, 1972) is the baseline for this work. It identifies the key functions of a PLSS and the components that provide those functions, including oxygen storage (at 850 psi in the main tanks and 6000 psi in the emergency tanks), heat rejection (by water sublimation), power (from batteries), and CO_2, humidity, and trace gas contamination control devices. Updating the component technologies in the existing schematic and recreating the schematic from the ground up via functional decomposition (design by evolution) were key tasks of this work.

METHODOLOGY

Using a system level, top-down approach to defining a PLSS (Ullman 2003, Shisko 1995, Blanchard 1998), the system's functional requirements were decomposed to their lowest level, creating a function structure for the PLSS. Combining the lowest level functions and user requirements, we created the operational performance requirements for the PLSS (Essex 1988, Essex 1989, Johnson Space Center Crew and Thermal Systems Division 1999).

The top-down approach was initiated with a thorough review of the PLSS schematic. Updates based on prior experience and development were incorporated, as well as requirements for the behavior of components (expressed in terms of the function provided by that part). Component performance was analyzed to identify functional characteristics, and functional behaviors were then described in greater detail and made specific through refinement (functional decomposition). Finally, the appropriateness of chosen functional elements was verified by re-synthesizing the original system, beginning with the lowest tier of functions and working back to the top of the function structure.

The top-down approach recognizes that general functions are involved in transforming inputs into outputs. The PLSS schematic currently in use was abstracted to the underlying general (functional) case, which consisted of several interacting functional elements (necessary functions were determined). The use of functional elements (abstraction) is the essential difference between a systems engineering methodology and integration of specific components. A particular functional element is applicable to a whole class of systems. Consequently, only a few such elements are needed to represent many real systems, for example, various alternatives for a PLSS schematic. Functional elements allow one to engage in system design before physical manifestations have been defined.

The top-down process has two main characteristics. First, the process is applicable to any part of the system. Starting with the overall PLSS, repeated application of this process at lower levels will result in decomposition of the system into smaller and smaller elements. Second, the process is self-consistent. External properties of the PLSS, as described by the inputs and outputs and relations between parts, must be reproduced by the external properties of the set of interacting elements, because they have been developed from the total system and are traceable back to the top need.

After identifying viable technologies that could satisfy the functional and performance requirements, they were grouped into schematics. In creating these schematics, we focused on four key functions of the PLSS -- oxygen supply, waste removal, thermal control, and power. Three time frames (2005, 2010, and 2020) were considered in this process. Only technologies that were expected to be at or beyond NASA Technology Readiness Level (TRL) 6 by each need date specified were considered. Three environments (zero-g, Lunar surface, and Martian surface) were also considered.

The next step in assessing the PLSS concepts was to analyze the options with EVASSAT. We used these results to perform both absolute and relative evaluations of all PLSS concepts developed. The schematics that met the evaluation criteria were assessed in detail to rank their relative merit.

FUNCTION STRUCTURE

A functional decomposition is used to break a device into its functions, typically using a hierarchical structure starting at the overall function of the device and progressively parsing functionality down to the most basic level. Functional decomposition is used widely in industry (the automotive and aircraft industries in particular) for designing new or improved products. This function structure served as the cornerstone for the remaining work on this study, forming, in conjunction with customer specifications, the basis for the evaluation criteria and systems analysis. It also served as the springboard for brainstorming innovative PLSS schematics. Figure 1 shows the first three tiers of the function structure that was created for this project.

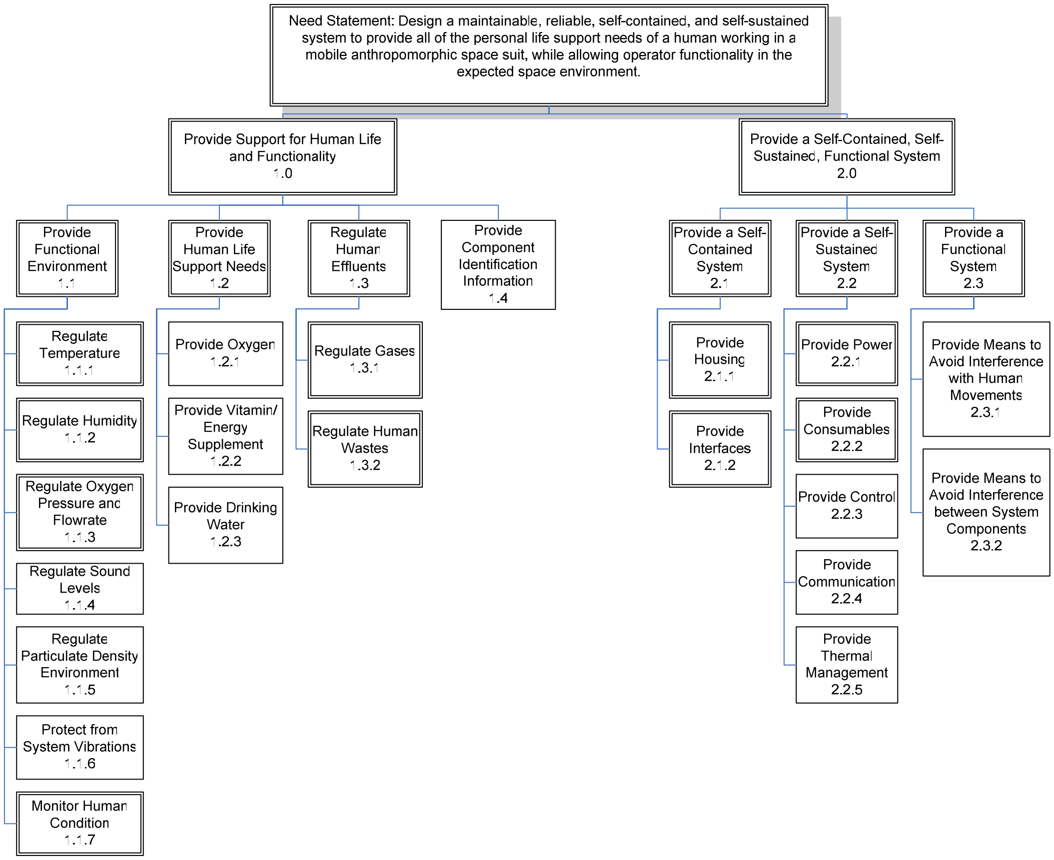

Figure 1. Third level function structure for PLSS.

EVALUATION CRITERIA

After identifying alternative technologies and integrated system concepts, the next step was to evaluate them against a set of criteria. Evaluation criteria for components, assemblies, and PLSS schematics were developed after the function structure was completed. Consistent with the Sutton study (Sutton, 1972), three layers of criteria, ranging from Go/No-go (e.g. safety, human factors) to Primary (e.g. mass, volume), to Secondary (e.g. commonality) were initially developed. Later discussions led us to combine the Primary and Secondary criteria into one weighted set of relative criteria. The TEES team, in conjunction with NASA, created the criteria to assure an unbiased evaluation of each schematic concept.

Safety was the primary Go/No-go evaluation criterion. Safety encompassed all aspects of flight, ground, and ancillary operations. The other Go/No-go criteria were performance (can the technology do the job required?), TRL (can the technology get to TRL 6 by the need date?), and crew invasiveness (how much does the technology interfere with the astronaut?). These criteria were applied at the component level to eliminate component technology concepts that did not meet the Go/No-go evaluation criteria.

The relative criteria (in order of weighting) were: reliability, robustness, safety, operability, PLSS mass (on-back), PLSS volume (suit), PLSS mass (systemic), commonality, PLSS volume (systemic), life cycle cost, multiple mission use, effort to TRL 6, and spin-off capability. These criteria were used to rank those schematics which survived the Go/No-go evaluation and the first round of mass and volume screening.

RESULTS

COMPONENT TECHNOLOGY BRAINSTORMING

TEES team members and NASA personnel spent 2 days participating in a structured brainstorming exercise (Osborne 1993, Adams 2001) to identify component technology concepts for three main functions of the PLSS: 1) atmosphere, 2) thermal control, and 3) power. After the brainstorming, TEES evaluated the proposed concepts and eliminated some for safety or TRL reasons. The remaining concepts were evaluated by TEES and NASA personnel for performance and crew invasiveness, which led to additional concepts being removed from consideration. The remaining component technology concepts formed the pool we used to create schematics. Those component concepts that were actually used in a schematic concept are listed in Tables 1-5. Where further analysis led to the elimination of a component technology, the primary reasons for that elimination are listed in the appropriate Tables.

Table 1. Oxygen storage concepts.

O2 Storage/Generation	Reason for Rejection
Compressed O2 tanks (3000psi)	
Cryogenic storage	
Lightweight Tanks	
Lung Powered System	
KO2	
Liquid N2O	**Too heavy (21.5 Kg)**
Photodissociation	**Too much power required (2kW) => too much mass for the power system**

Table 2. Waste Management/Removal Technologies.

CO2/H2O Management	Reason for Rejection
Rapid Cycling Amine + Carbon Filter (Trace Gas)	
Charcoal Filter	
Desiccant	
Functional Carbon Molecular Sieve	**Good concept but appears to be inferior to the RCA. Needs 66.7W of power versus 0.7W for the RCA for about the same mass**

Table 3. Power technologies.

Power	Reason for Rejection
Lithium Ion Batteries	
Lithium Sulfur Batteries	
Flywheels	**Too heavy (3.97Kg for 29.7W), rotating equipment can also create stability problems (2 opposing wheels needed to keep balance)**
Fuel Cells	**Batteries are still the most adapted, and have higher TRL**
Brayton Cycle	**Too heavy, not adapted to the power levels considered**

Table 4. Thermal energy rejection technologies.

Rejection	Reason for Rejection
H2O Sublimator	
Freeze Tolerant Radiator	
Mechanical Heat Pump	
Carbon Composite Radiator	
Gas Gap Radiator	
CO2 Sublimator	**Too heavy (~15Kg). At ambient pressure the CO2 sublimates with no heat load**
Variable Emissivity Radiator	
Martian H2O Evaporator	
Thermoelectrics	**Too bulky and heavy. Require too much power**
Compressed CO2	**Too heavy (both compressor and CO2 storage options)**

Table 5. Thermal energy transport technologies.

Heat Transport	Reason for Rejection
Heat Pipes	
2 phase Flow	
Higher K Tubing Garment	
Phase change material	**Added mass for little gain in expendables**

INITIAL SCHEMATIC CONCEPTS

Using a pared down version of the function structure that focused on four key functions - oxygen supply, power, thermal control, and waste removal (which included CO_2 control, humidity control, and trace contaminant removal) - and the component technologies from the brainstorming activity, we held a schematic concept creation brainstorming session and generated 10 PLSS concepts. With variations in the technologies selected for key functions, the number of concepts expanded to 25 (including the current PLSS schematic). These concepts were input to EVASSAT for evaluation. The key components of these schematics are listed in Table 6.

The nomenclature for describing the schematic concepts uses 3 identifiers. First, the S# indicates the time frame at which the components of the schematic will reach TRL 6 (1=2006, 2=2010, 3=2020). Second, the middle letter (Z=zero gravity, L=Lunar surface, or M=Martian surface) indicates the environment for which the schematic was constructed. Third, the ending number identifies the sequence in which the schematics were created, with letters appended to indicate major revisions of a basic schematic.

Table 6. Initial PLSS Schematic Concepts

Concept	Description
Baseline	Current PLSS design
S1-Z1A	Cryo O2, Fuel cell, Separator, water sublimator, single phase LCG, RCA
S1-Z1B	Same as S1-Z1A but Condensing HX instead of separator
S1-Z2	Lightweight O2 tank, lithium Ion battery, Freeze tolerant radiator, water sublimator, flexible heat pipes instead of
S1-Z2A	Same as S1-Z2 but circulating fan is removed and mask is used for lung powered air circulation
S2-Z1 - S2-L1	Cryo O2, Frozen CO2 and H2O are vented, variable emissivity radiator
S2-Z1C - S2-L1C	Same as S2-Z1A but the CO2 and H2O are removed by molecular sieve and a water sublimator assists the radiator for heat rejection
S2-Z2 - S2-L2	High pressure O2 storage, Fuel cell, Thermoelectric devices all over the suit to reject heat, two phase LCG,
S2-Z2A - S2-L2A	Same as S2-Z2 but the thermoelectrics all over the suit are replaced by a radiator with a mechanical heat pump that raises the radiator's temperature
S2-Z3 - S2-L3	Liquid N2O for oxygen (N2 is vented), flywheel, phase change heat storage, water sublimator, two phase flow LCG, Amine RCA
S2-Z4 - S2-L4	KO2 to O2 generation, Lithium Ion batteries, Gas gap radiator, Water sublimator, single phase LCG, Charcoal filter, Desiccant
S2-Z5 - S2-L5	Liquid N2O for oxygen, Open Brayton Cycle (run by N2 that is then vented - Sized on O2 breathing requirement), Mechanical heat pump raising radiator temperature to increase radiative heat rejection capability, LiOH,
S2-Z5A - S2-L5A	Same as S2-Z5 but Brayton cycle is dimensioned based on power requirements and CO2 and H2O are vented
S3-M1	Oxygen from photo-disassociation, powered by a Brayton cycle, heat is evacuated by forced convection from martian air forced through a compressor and then vented, high performance LCG
S3-M1A	Same as S3-M1 but compressor is replaced by a compressed CO2 tank.
S3-M2	Cryo O2, Fuel cell, CO2 sublimator from dry ice created at the base, RCA
S3-M2A	Same as S3-M2 but CO2 sublimator is replaced by compressed CO2

Total	
25	(including baseline)

EVASSAT ANALYSES

The Extravehicular Activity System Sizing Analysis Tool (EVASSAT) is a system level program that allows the user to size Extravehicular Activity System architectures. The program was developed within Microsoft Excel using the Visual Basic programming tool. The Extravehicular Activity System (EVAS) includes the Suit System, Airlock, Tools and Translation Aids, and EVA Vehicle Support Equipment. The thermal environment in which the Suit System resides is also user-specified. Based on user inputs, the program will predict power, mass, and volume requirements at both the system and subsystem levels. A mass balance is performed to track consumable items and to size related equipment. A heat balance was performed to determine the total system design cooling rate and equipment heat generation.

We used EVASSAT to evaluate the schematics created in this project. Doing so required the creation of a number of additional subroutines to handle the divergent technologies examined in this effort. Table 7 shows the results of the first round of EVASSAT analyses. Half the schematic concepts were eliminated for various reasons, primarily for being too massive, as shown in Table

Table 7. Second Round of Schematic Concepts.

Concept	Description
S1-Z1A	RETAINED, combined with S1-Z1B into S1-Z1 Rev 1
S1-Z1B	RETAINED, combined with S1-Z1A into S1-Z1 Rev 1
S1-Z2	RETAINED, became S1-Z2 Rev 1 and Rev 2
S1-Z2A	RETAINED, became S1-Z2A Rev 1 and Rev 2
S2-Z1 - S2-L1	ELIMINATED, required cryogenic O2 to freeze CO2 and H2O too high
S2-Z1C - S2-L1C	RETAINED, became S2-Z1C Rev1 and S1-L1C Rev1
S2-Z2 - S2-L2	ELIMINATED, too heavy, too much power needed
S2-Z2A - S2-L2A	RETAINED became S2-Z2A Rev1 and S2-L2A Rev1
S2-Z3 - S2-L3	ELIMINATED, too heavy
S2-Z4 - S2-L4	RETAINED, became S2-Z4
S2-Z5 - S2-L5	ELIMINATED, too heavy
S2-Z5A - S2-L5A	ELIMINATED, too heavy
S3-M1	ELIMINATED, too heavy, too much expendables and power
S3-M1A	ELIMINATED, too heavy, too much expendables and power
S3-M2	RETAINED, combined with S3-M2A into S3-M2 Rev1, S3-M2 Rev2, and S3-M2 Rev3
S3-M2A	RETAINED, combined with S3-M2 into S3-M2 Rev1, S3-M2 Rev2, and S3-M2 Rev3

Total	**24**
RETAINED	**12**
ELIMINATED	**12**

FINAL SCHEMATIC CONCEPTS

Once the EVASSAT analyses were completed, the remaining schematic concepts were revised to reduce their mass (primarily) and/or volume and/or power demand (secondarily). In addition, the concepts were sized to accommodate the worst case environments they would encounter.

We also began developing the interfaces for the schematic concepts at this point. During the interface development process, further minor variations were identified which did not significantly affect mass or volume, but did affect one or more of the relative evaluation criteria discussed above. Between all of the stages of this project, over 40 PLSS concepts were defined and analyzed.

Tables 8-10 show the EVASSAT mass results for each of the three main environments considered. Note that these are component-only masses and do not include structure. Those cases using a radiator would be slightly lower in mass compared to the other cases once structure is considered, since the radiator can form part of the structure. The “1 EVA” mass numbers indicate the on-back weight an astronaut would have to carry using that particular PLSS, while the “10 EVA” mass numbers indicate the amount of mass the overall mission would have to bring to the surface to support multiple EVAs using a particular PLSS.

Schematic diagrams of the final system concepts are included in the Appendix.

Table 8. EVASSAT mass results for zero-g (station) cases.

	Total mass for 1 EVA (Kg)	Difference (Kg)	Expendables saved each EVA (Kg)	Mass for 10 EVAs (kg)
Baseline	27.91			**68.11**
S1-Z1 Rev1	23.17	-4.74	3.01	**36.31**
S1-Z1 Rev2	23.97	-3.94	2.73	**39.63**
S1-Z2 Rev1	29.28	1.37	3.22	**40.51**
S1-Z2A Rev1	26.54	-1.37	3.28	**37.25**
S2-Z1C Rev1	24.73	-3.19	3.14	**36.68**
S2-Z1C Rev1a	23.82	-4.09	3.20	**35.24**
S2-Z2A Rev1	32.06	4.14	4.05	**35.79**
S2-Z4 Rev1	38.42	10.51	-0.28	**81.16**

Table 9. EVASSAT mass results for Lunar surface cases.

	Total mass for 1 EVA (Kg)	Difference (Kg)	Expendables saved each EVA (Kg)	Mass for 10 EVAs (kg)
Baseline	27.56			**66.89**
S2-L1C Rev1	28.24	0.68	0.88	**59.63**
S2-L1C Rev1a	27.36	-0.20	0.94	**58.21**
S2-L2A Rev1	34.04	6.48	3.96	**37.77**

Table 10. EVASSAT mass results for Martian surface cases.

	Total mass for 1 EVA (Kg)	Difference (Kg)	Expendables saved each EVA (Kg)	Mass for 10 EVAs (kg)
Baseline	24.36			**62.95**
S3-M2 Rev1	44.60	20.24	-11.61	**187.69**
S3-M2 Rev3	33.01	8.65	3.87	**36.75**

RELATIVE EVALUATION

Using the relative evaluation criteria described above, TEES and NASA scored the final schematic concepts. The summary results of this scoring are in Table 11. "Rank" is the numerical order of the scores, while "Group" indicates the clustering of the scores. Groups A and B were above average, while Groups C and D were below average. The scores for mass and volume are scaled from the EVASSAT results, while the scores for all other criteria were generated by consensus among TEES team members and NASA personnel.

Table 11. Relative Evaluation Scoring of PLSS Concepts.

Criterion	weight	S1-Z1 R1	S1-Z1 R1A	S1-Z1 R2	S1-Z2	S2-Z1C R1	S2-Z1C R1A	S2-Z2A R1	S2-Z4	S3-M2 R3
Reliability	0.136	11.4	13.4	10.4	10.4	10.4	11.4	12.4	15.4	4.4
Robustness	0.122	10.9	14.9	7.9	10.9	7.9	8.9	14.9	11.9	11.9
Safety	0.108	11	11	10	13	11	10	10	13	11
Operability	0.096	10.7	14.7	8.7	10.7	9.7	11.7	12.7	7.7	13.7
On-suit mass	0.095	16.4	16.4	15.6	10.3	13.1	14	6.5	1.1	6.6
On-suit volume	0.074	14.1	14.1	9.5	11.6	11.8	13	13.5	0.3	12
system mass	0.072	12.4	12.4	11.7	12.9	9.2	9.6	15.3	1.1	15.3
commonality	0.07	12.2	12.6	13.1	12.6	12.2	13.6	10.7	0.3	12.6
system volume	0.06	12.9	12.9	12.9	10.9	11	15.4	11.4	1.9	10.9
life cycle cost	0.054	10.7	10.7	9.7	10.7	10.7	9.7	10.7	16.7	10.7
multiple uses	0.054	10	10	8	12	12	10	13	13	12
effort to TRL 6	0.048	14.9	16.4	13.4	9.9	9.9	9.9	10.4	3.4	11.4
spinoff capability	0.012	10.1	10.1	10.1	11.1	11.1	11.1	14.1	11.1	11.1
Overall		12.15	13.4	10.71	11.29	10.6	11.35	11.88	7.91	10.59
Rank		2	1	6	5	7	4	3	9	8
Group		A	A	C	B	C	B	A	D	C

DISCUSSION

The results of the relative evaluation showed a significant bias towards "in hand" or near-term technology. The two highest scoring schematics (S1-Z1 Rev 1 and S1-Z1 Rev 1A) are very modest evolutions of the existing PLSS.

The overall ratings for the schematics divided into 4 groups, each of which will be discussed in turn.

In the first group there are three concepts (S1-Z1 Rev 1 and Rev 1A and S2-Z2A/L2A). S1-Z1 Rev 1 used 3000 psi oxygen tanks, a rapid cycling amine bed (RCA) for CO_2 and humidity control, a two-phase liquid cooling and ventilation garment (LCVG) for heat transport, Li-ion batteries for power, and a water sublimator for thermal control. S1-Z1 Rev 1A differed from S1-Z1 Rev 1 only in using a single phase LCVG. S2-Z2A (and S2-L2A, which was identical) used 3000 psi oxygen tanks, a RCA, a two-phase LCVG, LiS batteries, and a mechanical heat pump coupled to a carbon composite radiator.

These concepts were clearly above average in their overall scores, with both S1-Z1 concepts ranking highest in on-suit mass and volume. S1-Z1 Rev 1A and S2-Z2A ranked highest in reliability. S2-Z2A ranked highest in system mass, since it's use of a heat pumped radiator eliminated any thermal system expendables. All three concepts ranked fairly well in robustness and operability. The chief weaknesses of this group included a poor on-suit mass score for S2-Z2A; it should be noted, though, that the radiator in this concept could form the outer structure of the PLSS as well, meaning the present mass comparison (which does not account for structure mass) penalizes S2-Z2A (and the other concepts that use a radiator) relative to those concepts which do not use a radiator. Both S1-Z1 concepts did poorly in multiple use evaluations, and S1-Z1 Rev 1 received a mediocre reliability score, mainly due to concerns about the reliability of its two-phase LCVG.

In the second group there are two concepts (S1-Z2 and S2-Z1C/L1C Rev 1A). S1-Z2 used lightweight 850 psi oxygen tanks, a RCA, loop heat pipes (LHP) for heat transport, Li-ion batteries, and a freeze-tolerant heat exchanger tied to LHP radiators, backed up by a water sublimator for heat rejection. S2-Z1C Rev 1A (and S2-L1C Rev 1A, which was identical) used cryogenic oxygen storage, a RCA, a two-phase LCVG, LiS batteries, and a variable emissivity radiator with water sublimator backup for thermal control. The heat needed to warm the cryogenic oxygen came from systemic waste heat to reduce the amount of heat rejection required.

These concepts overall scores were above average, but not by much. The strengths of S1-Z2 lay in safety (lower pressure oxygen tanks), system mass, commonality, and multiple uses. Its weaknesses included volume (on-suit and system) and effort to TRL 6. The strengths of S2-Z1C Rev 1A included operability, on-suit mass and volume, commonality, and system volume. Its weaknesses included reliability, system mass, life cycle cost, and effort to TRL 6.

In the third group there are three concepts (S1-Z1 Rev 2, S2-Z1C/L1C Rev 1, and S3-M2 Rev 3). S1-Z1 Rev 2 replaced the 3000 psi oxygen tank with cryogenic liquid oxygen storage, with all other components being the same as S1-Z1 Rev 1. S2-Z1C Rev 1 used 3000 psi oxygen tanks instead of cryogenic liquid oxygen storage, with all other components being the same as S2-Z1C Rev 1A. It is interesting to note that, in one case, the use of cryogenic oxygen instead of high pressure gaseous oxygen increased the concept's score, while in a second case it decreased the concept's score. S3-M2 uses 3000 psi oxygen tanks, a RCA, LiS batteries, and a heat pumped variable emissivity radiator. S3-M2's strengths were reliability, operability, system mass, and commonality. Its weaknesses were robustness, on-suit mass and system volume.

The fourth group consists of a single concept, S2-Z4/L4. This concept uses KO_2 to both generate oxygen and remove CO_2, a desiccant to remove humidity, LiS batteries, and a gas gap radiator backed up by a sublimator for thermal control. Its strengths were reliability, robustness, safety, life cycle cost, and multiple uses. Its weaknesses were operability, on-suit mass, on-suit volume, system mass, commonality, system volume, and effort to TRL 6.

RECOMMENDATIONS

The top four schematics created in this study were: 1) S1-Z1 Rev 1 (combined with S1-Z1 Rev 1A, given the very small differences between them), 2) S2-Z2A/L2A, 3) S2-Z1C/L1C Rev 1A (and could include the 3000 psi gaseous storage from Rev 1), and 4) S1-Z2.

Key technologies to pursue based on these schematics include: 1) low mass 3000 psi oxygen storage, 2) RCA improvements, 3) Li-ion and LiS batteries, 4) radiator technology, and 5) a mechanical heat pump. Cryogenic oxygen is also important, but appears to be lower priority than gaseous storage. Two-phase LCVG technology (mechanically or capillary pumped) would be beneficial, but appears to be lower priority than the preceding technologies.

This list of schematics and technologies offers a roadmap for evolving the PLSS. In the first stage (S1-Z1), development of high pressure oxygen tanks and RCA technology allows replacement of the current low pressure oxygen tanks and LiOH canister. In the second stage (S2-Z2), LiS batteries supplant Li-ion batteries while radiators (with a mechanical heat pump when ready) replace the water sublimator (which stays on to supplement the radiator in hot environments prior to deployment of the heat pump). In the third stage, lightweight, high pressure oxygen tanks or cryogenic liquid oxygen storage are used. Two-phase LCVG technology may be inserted into the PLSS at whichever stage it is deemed ready. This roadmap is depicted schematically in Figure 2.

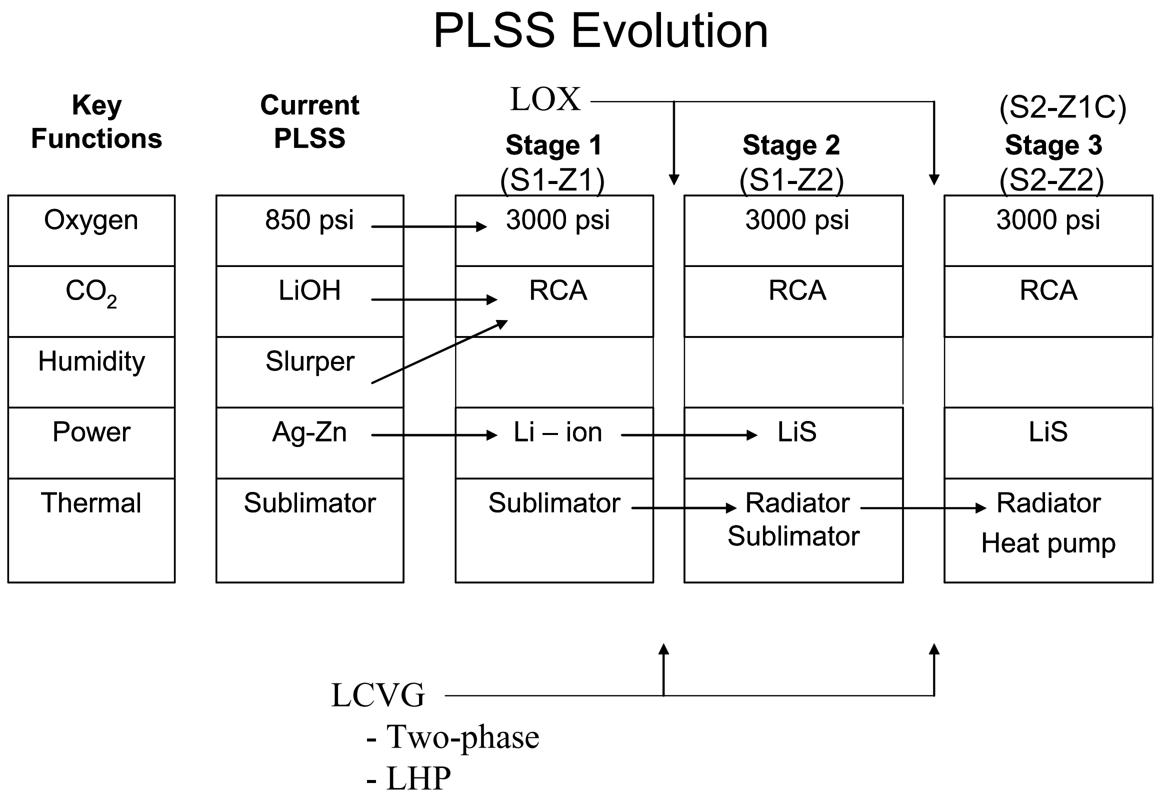

Figure 2. A Potential PLSS Evolution Scheme

SUMMARY

A team led by TEES completed a preliminary design and analysis of PLSS concepts for use on future NASA missions. A number of component and system concepts that reduce the mass (both on-back and overall system) of the PLSS have been identified. A technology development roadmap that provides a path to evolve the PLSS from its current form to a form better suited to supporting long duration Lunar and Martian surface exploration missions has been recommended.

The Apollo PLSS design team did an excellent job, creating a low mass, low volume PLSS and it was very difficult to improve on their work. In fact, the highest rated concept (S1-Z1 Rev 1) can be viewed as the Apollo PLSS with higher pressure oxygen tanks and a RCA in place of the LiOH canister.

CONCLUSIONS

The use of improved or emerging technologies in the PLSS should result in reduced mass and volume compared to the existing system.

Within very broad limits, most of the technologies examined in this study are interchangeable. In particular, the various types of radiators can be used interchangeably. The oxygen supplies are readily interchangeable at this stage of design, but become less so as hardware is built. Some benefit may be gained using two-phase heat transport, including multiple capillary pumped units instead of a unitary mechanically pumped system. Again, it is relatively easy to swap out these technologies at the design stage, but differences between capillary and mechanically pumped devices reduce this interchangeability as hardware is built.

Development of a low mass, high reliability, high coefficient of performance heat pump for use with a radiator could save significant overall launch mass (cost) for long duration Lunar missions and especially for Martian missions.

Performance and power demand for the PLSS do not justify the use of power supplies other than batteries. The short EVA time frame and modest energy demands found in this study are easily met by existing battery technology; improved battery technology, however, would provide additional mass, volume, and power availability advantages. The ability to reject heat is a key limitation on the amount of power useable in a PLSS/spacesuit.

ACKNOWLEDGMENTS

This work was supported by the Crew and Thermal Systems Division of NASA's Johnson Space Center and funded under contract NNJ05HB41B (DO-001). TEES' team included faculty, staff, and students at Texas A&M University's Center for Space Power, faculty and students at the University of Colorado, Boulder, Independent Design Analysis, MTS Global, Dittmar Associates, Inc., and Muniz Engineering, Inc.

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APPENDIX

Schematic Diagrams

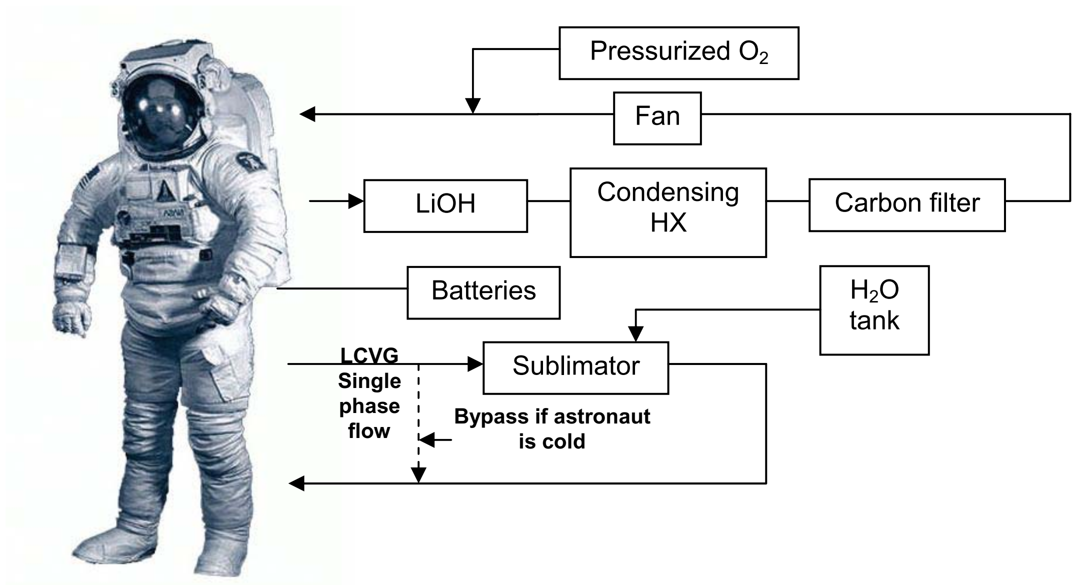

Figure 3. Baseline Schematic Overview

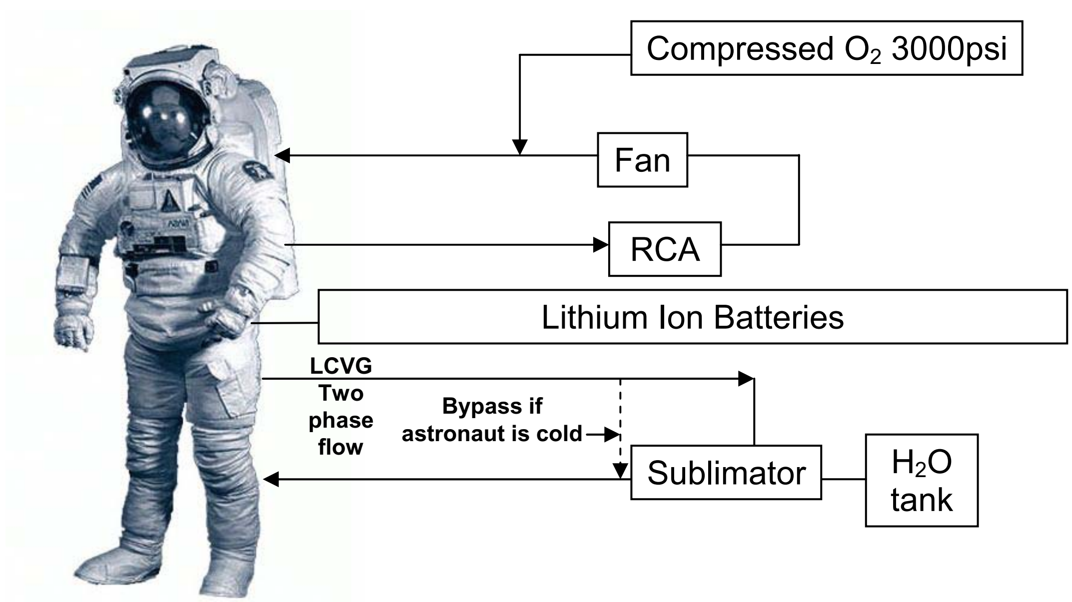

Figure 4. S1-Z1 Rev 1 Schematic Overview

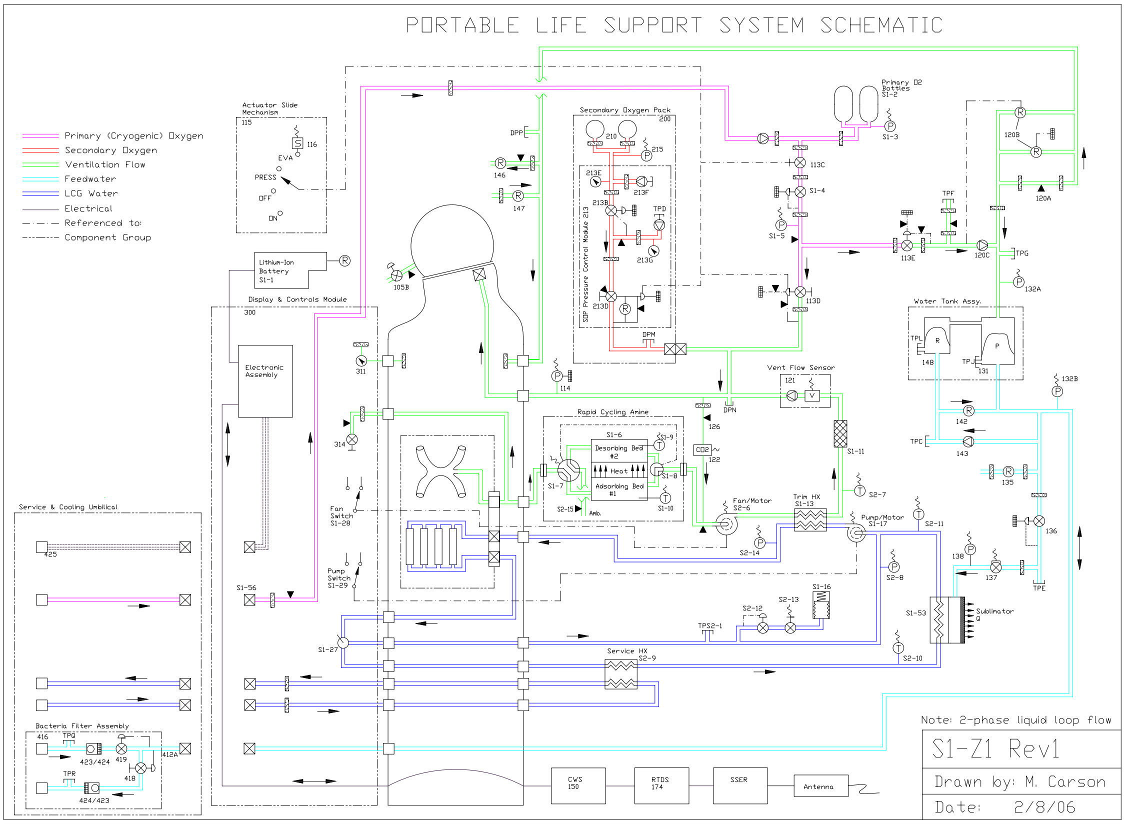

Figure 5. S1-Z1 Rev 1 Schematic

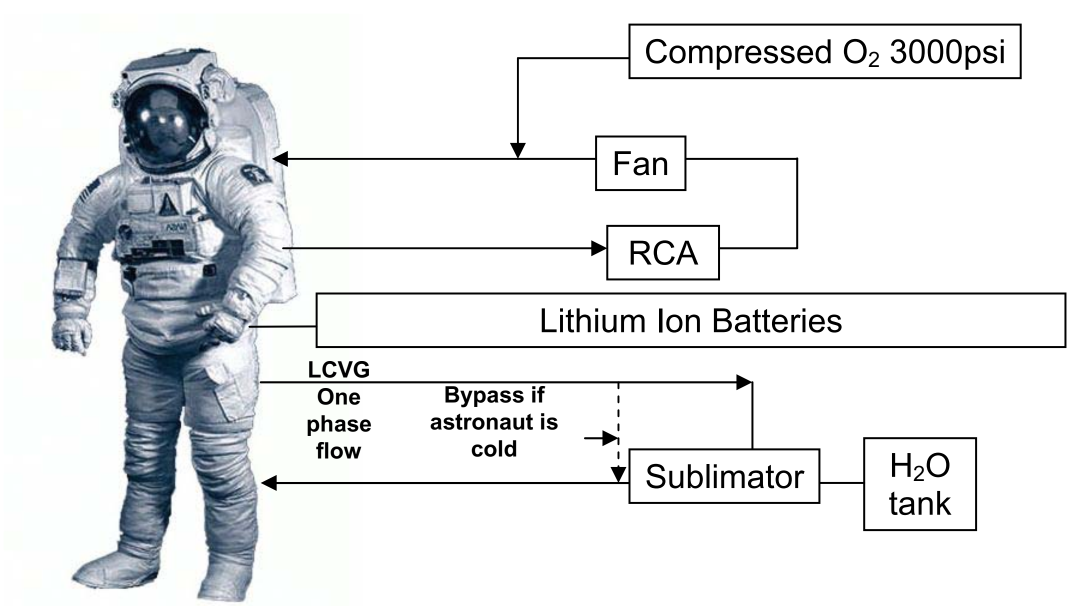

Figure 6. S1-Z1 Rev 1A Schematic Overview

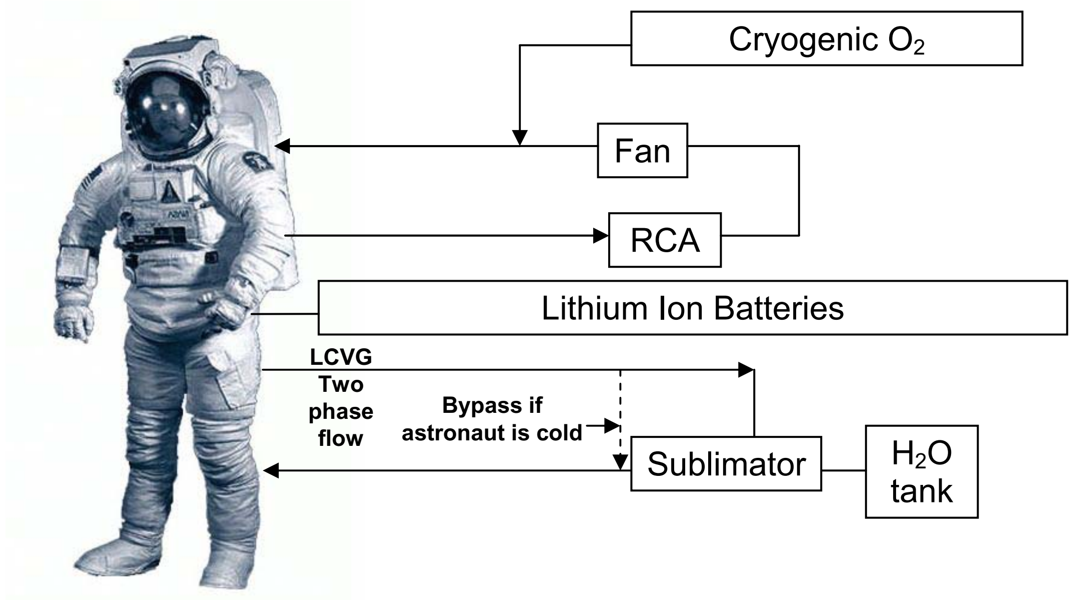

Figure 7. S1-Z1 Rev 2 Schematic Overview

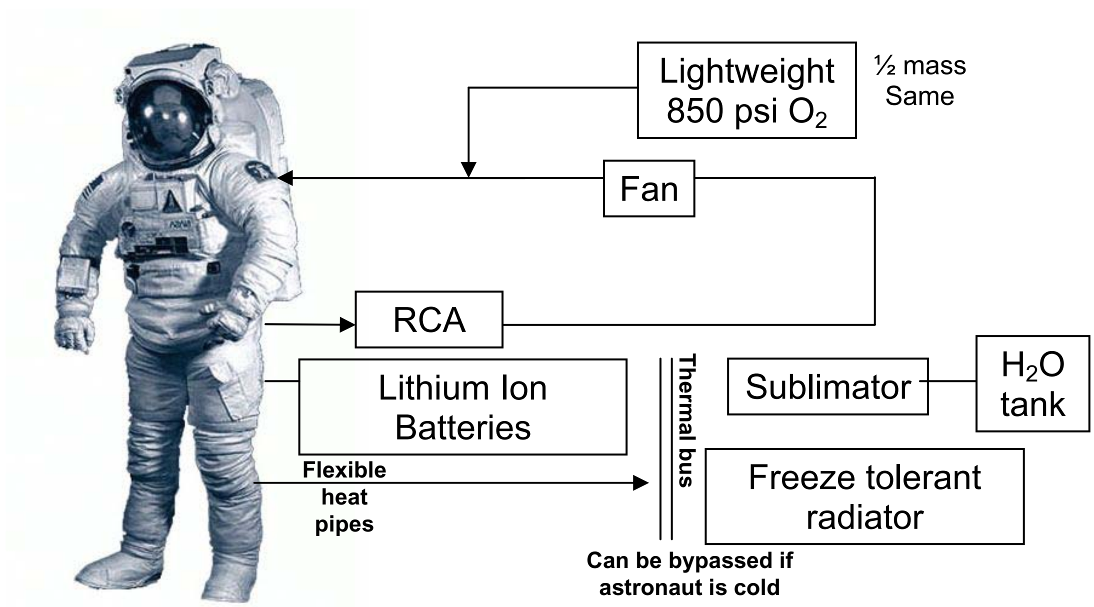

Figure 8. S1-Z2 Rev 1 Schematic Overview

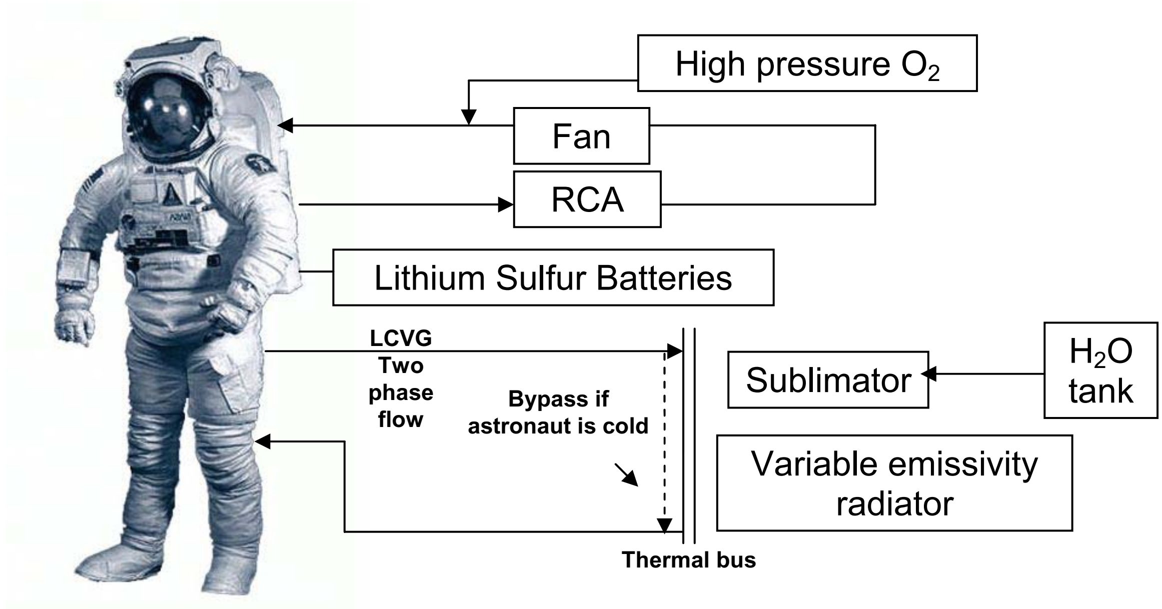

Figure 9. S2-Z1C/L1C Rev 1 Schematic Overview

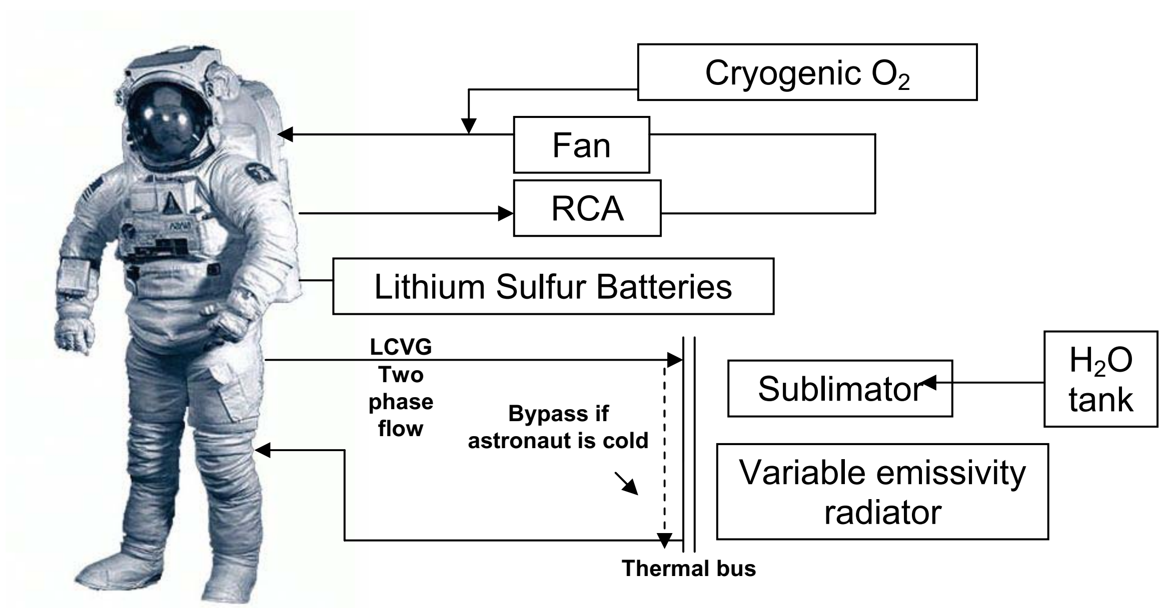

Figure 10. S2-Z1C/L1C Rev 1A Schematic Overview

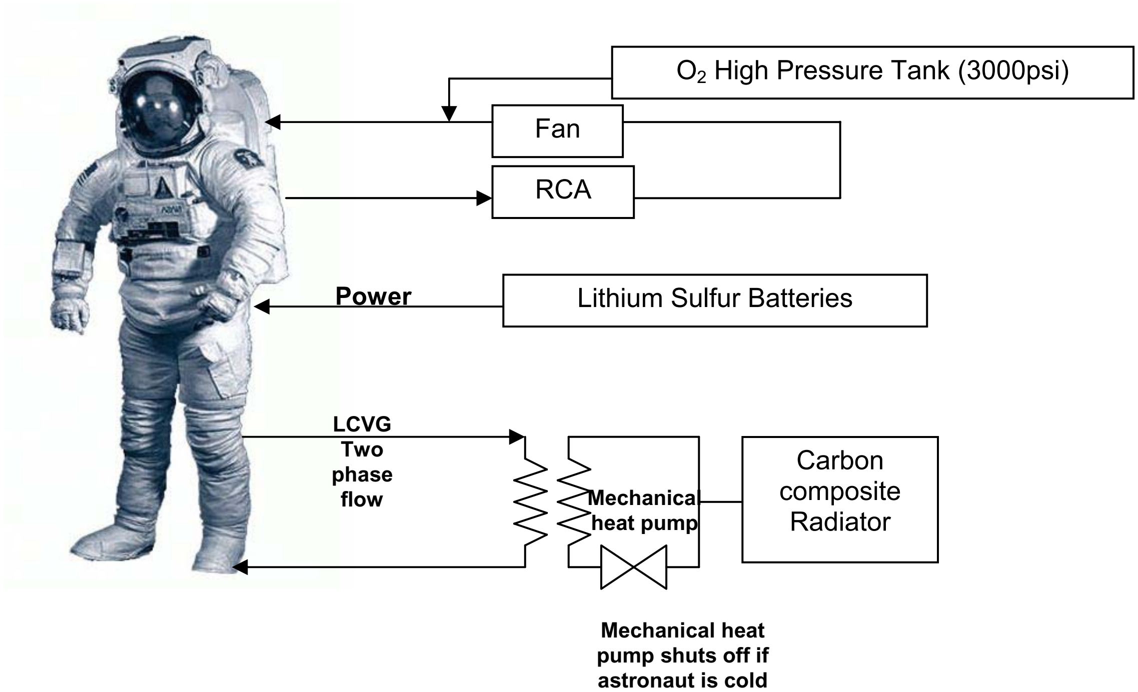

Figure 11. S2-Z2A/L2A Rev 1 Schematic Overview

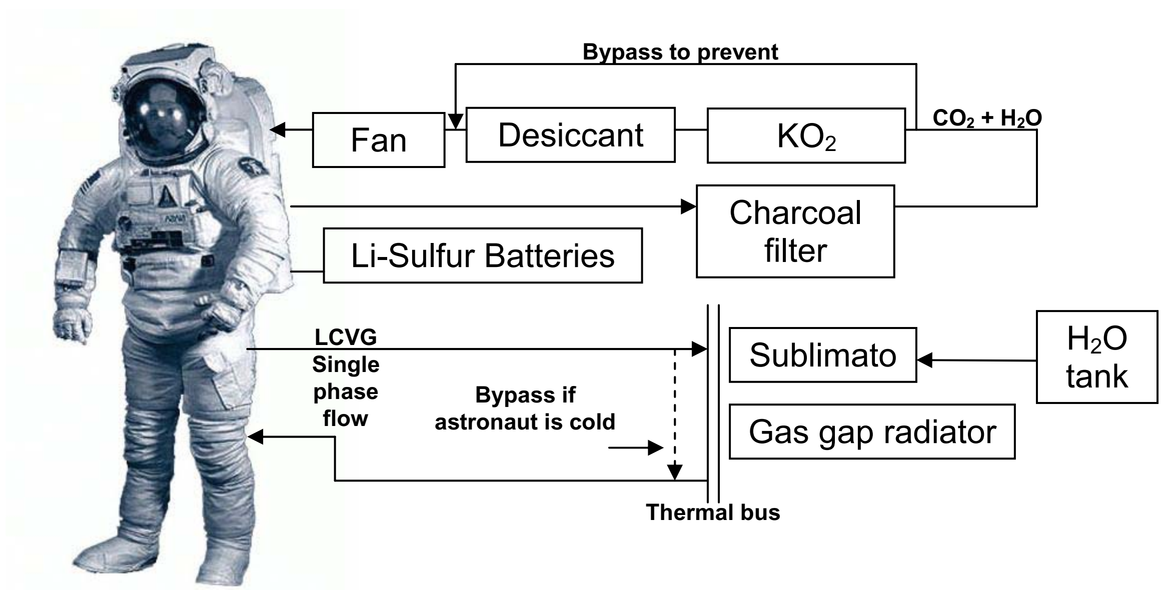

Figure 12. S2-Z4/L4 Rev 1 Schematic Overview

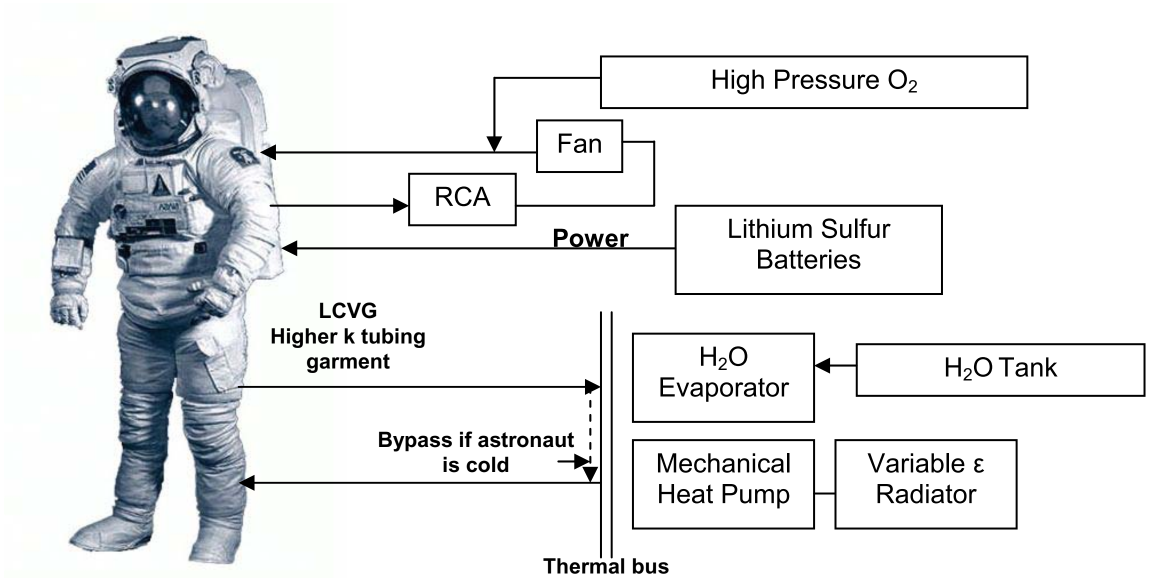

Figure 13. S3-M2 Rev 3 Schematic Overview