54th International Conference on Environmental Systems
13-17 July 2025, Prague, Czech Republic
ICES-2025-90

Martian Exploration Portable Life Support System Schematic Study

Dana M. Lobmeyer, Ph.D.[1], Madeleine Oliver, Ph.D.[2], Emma J. Quick[3], Olivia J. Lawson[4], Lawrence W. Barrett, Ph.D. [5], Bruce C. Conger[6]
Amentum, Houston, Texas, 77058

Cinda Chullen[7] and Colin Campbell[8]
NASA Johnson Space Center, Houston, TX, 77058

The Mars environment poses unique challenges for portable life support system (PLSS) technologies supporting extravehicular activities (EVA) that necessitate modifications to the NASA baseline exploration PLSS (xPLSS) design. This work details a landmark schematic study conducted to identify and recommend the most promising Martian Exploration PLSS (mxPLSS) architectures for consideration and further evaluation. Conducted from January 2024 to September 2024, the study began with a blank sheet approach to pinpoint technologies that could potentially satisfy each mxPLSS major function. A comprehensive list of over 80 technologies was compiled. These technologies were filtered down based on mxPLSS guidelines established during the project and a preliminary equivalent system mass (ESM) analyses under nominal Martian environmental conditions. By considering only unique combinations of the most feasible technology options, seven mxPLSS schematics with the lowest overall mass were identified. Evaluation and comparison of each schematic was subsequently performed using a newly developed PLSS sizing tool: the Guided Utility Sizer (GUS). This paper summarizes the study approach, schematic selection process, and final assessment that culminated in three different schematic recommendations. Recommended mxPLSS schematics are described relative to the vehicle architecture they would require.

Acronyms and Nomenclature

CHXR	=	condensing heat exchanger
CO_2	=	carbon dioxide
CSSE	=	Constellation Space Suit Element
ECLSS	=	Environmental Control and Life Support System
ECVG	=	Evaporative Cooling and Ventilation Garment
EMU	=	Extravehicular Mobility Unit
ESM	=	equivalent system mass
EVA	=	extravehicular activity
GOX	=	gaseous oxygen
GUS	=	Guided Utility Sizer
H_2	=	hydrogen
H_2O	=	water
ISRU	=	In-Situ Resource Utilization
MTSA	=	Metabolic Heat Regenerated Temperature Swing Adsorption
mxPLSS	=	Martian Exploration Portable Life Support System
M2M	=	Moon to Mars
PCM	=	phase change material
PLSS	=	Portable Life Support System
RCA	=	rapid cycle amine
SG	=	sweep gas
SME	=	subject matter expert
SWME	=	spacesuit water membrane evaporator
TCC	=	trace contaminant control

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[1] Thermal Analysis Engineer, 2224 Bay Area Blvd, Houston, TX 77058.
[2] Chemical Engineer, 2224 Bay Area Blvd, Houston, TX 77058.
[3] Chemical Engineer, 2224 Bay Area Blvd, Houston, TX 77058.
[4] Chemical Engineer, 2224 Bay Area Blvd, Houston, TX 77058.
[5] ECLSS Analysis Technical Lead, 2224 Bay Area Blvd, Houston, TX 77058.
[6] Senior Subject Matter Expert, 2224 Bay Area Blvd, Houston, TX 77058.
[7] Project Engineer, Crew & Thermal Systems Division, NASA JSC.
[8] EVA Technical Discipline Lead, Crew & Thermal Systems Division, NASA JSC.

LCAR = lithium chloride absorber radiator
LCVG = liquid cooling ventilation garment
LOX = liquid oxygen
MetOX = Metal Oxide
O_2 = oxygen
MOF = Metal Organic Framework
TRL = technology readiness level
VBA = Visual Basic for Applications
VE EC = variable emissivity electrochromic
xEMU = exploration extravehicular mobility unit
xPLSS = Exploration Portable Life Support System

I. Introduction

THE complicated environment on Mars poses unique challenges for extravehicular activity (EVA) that necessitate modifications to the current exploration PLSS (xPLSS) design at a minimum, and a possible redesign in the worst case. At an atmospheric pressure of approximately 0.15 psia and a composition of 95 percent carbon dioxide (CO_2), venting technologies originally designed for vacumm (i.e., rapid cycle amine (RCA) and spacesuit water membrane evaporator (SWME)) cannot perform effectively on Mars as they are currently designed. Moreover, thermal conductance from the gaseous Martian atmosphere, along with storms and seasonal weather changes, present an ever-changing thermal and radiative environment for which the current PLSS architecture is not fully capable of adapting to. At the same time however, the presence of gravity on Mars (0.38g) significantly reduces the on-back mass allowance for the mxPLSS, whose permissible mass and volume are already restricted by the large travel distance and long duration mission prerequisite to reaching the Martian surface. This consideration becomes paticularly important when regarding the consumables required for venting and non-regenerable technologies. To develop and build an mxPLSS, it is therefore necessary to determine the most promising technologies or technological modifications for the eight major functions of the PLSS that do not rely on venting to vacuum, maintain reliability in dynamic conditions, and optimize the mass and volume of the PLSS by incorporating characteristics like regenerability.

Schematic studies have historically been used to accomplish the daunting task of PLSS design and aid program roadmaps for EVA technology developments. The most recent schematic study prior to this work was conducted from 2005 to 2007 under the name Constellation Space Suit Element (CSSE) PLSS Schematic Study.[1] The CSSE study leveraged multiple groups, including industry and academia, to identify what are now the technologies that make up the xPLSS: gaseous oxygen (GOX) for O_2 storage and supply, RCA for combined CO_2 and humidity removal, liquid cooling ventilation garment (LCVG) and centrifugal fans for ventilation and flow drive, SWME for thermal control, activated charcoal beds for trace contaminant control, and lithium-ion batteries for power and energy storage. Prior to the CSSE study, schematic studies were also conducted for the Space Shuttle program and the Apollo program. In all cases, these extensive studies resulted in PLSS technology recommendations that guided the technology roadmaps of their time. In planning the development of the mxPLSS, a Mars PLSS roadmap (Figure 1) was developed[2] to meet the NASA Moon to Mars (M2M) timeline of achieving Mars surface exploration by the late 2030s.[3] Within this roadmap, a Mars schematic system study in fiscal year 2024 was determined to be necessary prior to Mars PLSS prototype and design. The schematic study presented here satisfies this objective and provided further guidance on the work necessary to meet the current timeline.

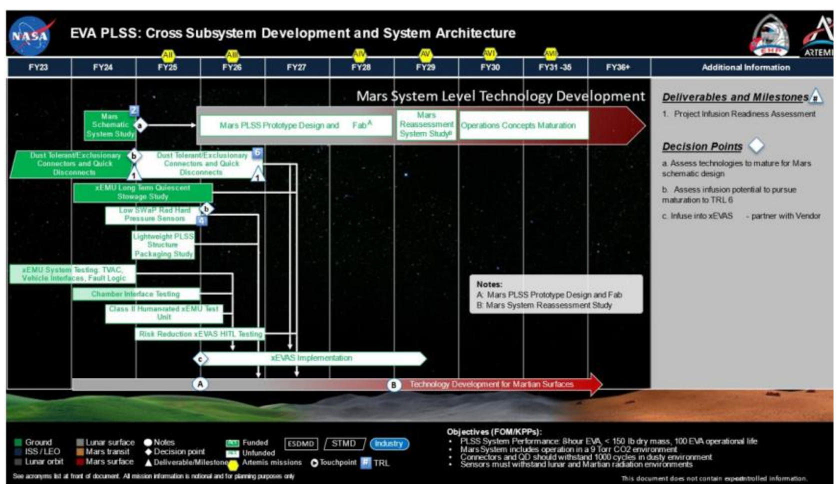

Figure 1. Cross subsystem and system architecture development roadmap for the EVA PLSS.

In this work, thermal and fluids engineering analyses have been utilized to coordinate and carry out a schematic study for the mxPLSS. Both the current exploration extravehicular mobility unit (xEMU) design and a blank sheet approach were considered to ensure that the recommended architecture represents the best plan known today. With the Martian environment in mind, this schematic study considers technologies for the eight major PLSS functions: O_2 storage and supply, ventilation network, flow drive (ventilation and thermal loop), CO_2 removal, humidity removal, thermal control, trace contaminant control, and power and energy storage. Given that the CO_2 removal, humidity removal, and thermal control functions of the xPLSS would not operate effectively on Mars as is, these functions have been investigated in the most detail.

II. Study Approach

The schematic evaluation began with a broad approach for identifying potential technologies for each PLSS major function, which were gradually narrowed down to arrive at seven schematic options for the mxPLSS. Technologies were down selected using criteria relevant to a PLSS, such as safety and feasibility, as well as Mars specific criteria, such as technology readiness level (TRL), low mass and volume, and regenerability. This down-selection process allowed for the identification of the most feasible and realistic technologies available to date, thereby reducing the number of schematics to be evaluated. The following section details the technology down-selection process, schematic selection process, and schematic analyses that guided the final recommendations.

A. Identification of Promising PLSS Technologies

A broad search was conducted to compile promising technologies that could satisfy at least one of the eight major functions of the PLSS. This intital investigation included technologies that had been used in a PLSS, technologies that were currently being investigated for a PLSS, and technologies that had potential but had yet to be investigated for a PLSS. This broad scope ensured no technology was eliminated prematurely. During this research effort, hundreds of NASA reports, ICES proceedings, previous schematic studies, and terrestrial journal articles were examined. The effort resulted in an extensive technology list that details 89 independent technologies with their associated advantages and disadvantages.[4] While not all the technologies were ultimately considered for schematics, the compiled list provides promising areas of research to keep in mind as technologies mature.

A breakdown of the number of technologies considered per major PLSS function is provided in Table 1. The initial technology list was presented to subject matter experts (SMEs) and collaborators to receive feedback prior to being narrowed down. Many of the technologies considered here are capable of satisfying more than one major function (e.g., the RCA performs both CO_2 and humidity removal).

Table 1. Breakdown by function of the number of technologies considered for the mxPLSS schematic study.

Function	Number of Technologies Considered
Oxygen storage and supply	8
Ventilation network	2
Flow drive (ventilation and thermal loop)	6
Carbon dioxide removal	22
Humidity removal	25
Thermal control	18
Trace contaminant control	8
Power and energy storage	19
Total independent technologies	**89**

B. Initial Technology Elimination

Two rounds of technology eliminations were conducted. The initial round was based on feedback from SMEs and collaborators prior to sizing and schematic considerations. These were conducted on a technology-by-technology basis and those eliminated at this stage of the study often had more than one reason for elimination. For example, CO_2 methanation for CO_2 removal was eliminated because it requires a significant amount of power to operate and generates particulate matter. A technology was immediately eliminated if it presented an obvious safety concern or had a low TRL/no TRL. "No TRL" technologies represent those in the early stages of development for non-space applications. Of the 89 initial technologies, 32 were eliminated at this stage; however, many of these eliminated technologies could become viable in the future through continued research efforts. The mechanical counter-pressure space suit,[5] for instance, was eliminated simply due to lack of research. Other technologies such as metal-organic frameworks (MOFs), a class of crystalline materials with ultrahigh porosities and surface areas[6], show a high degree of promise for adsorption and removal of CO_2, H_2O, and trace contaminants if researched and developed further for space-specific applications. To ensure time was spent on promising but underdeveloped technologies, a university study collaboration was set in place during this project to continue research on some technologies that fall into this category. The second round of eliminations was conducted prior to schematic formulation and can be found in the "Schematic Identification and Analysis Process" section below.

C. Establishment of mxPLSS Guidelines

Prior to forming schematic combinations from the filtered technology list, guidelines for the mxPLSS and schematic down-selection process were established and used as criteria for which technologies must meet to be further considered. PLSS requirements, such as environmental conditions and metabolic profiles, were defined and used to size relevant technologies, while assessment standards, such as figures of merit and operational concepts, were used to assess selected schematics and guide final selections. From this work, a miniature subsystem specification document outlining all requirements was created, and a list of assessment criteria, figures of merit, and operational concepts were outlined.[7,8]

D. Development of PLSS Sizing Tool: Guided Utility Sizer

The Guided Utility Sizer (GUS) was developed to perform sizing analyses of PLSS technology options when assembled in different schematic combinations.[9] This simplified and user-friendly tool performs the heat and mass balances for a user-selected PLSS schematic under a user-defined environment. Programmed within Microsoft Excel 2024 for ease of distribution and use, and operating across only six worksheets, the GUS tool computes the mass, volume, power consumption, and consumables requirements for selected technologies and associated PLSS architectures as a whole. Figure 2 depicts the interconnectivity of the six worksheets within GUS. Only the Schematic Evaluation sheet and the Design Parameters sheet require user input while the remaining sheets work together to auto populate the desired computations. The program operates almost entirely within the main worksheets, aside from two Visual Basic for Applications (VBA) macros. A detailed GUS User's Guide was developed that explains the GUS user interface and tool development, and outlines all mass and heat balance calculations that are executed within the tool.[10]

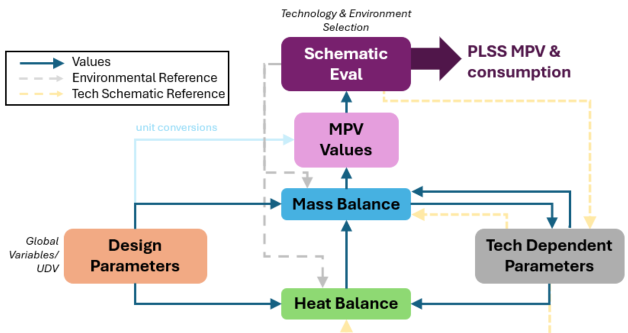

Figure 2. GUS worksheet flow diagram.

The user must only select the environment and technologies for the eight PLSS major functions on the Schematic Evaluation sheet to run the tool and size schematics. PLSS sizing can be executed for Martian, Lunar, station, and deep space environments, at corresponding hot, cold, nominal, or user-defined environmental conditions. Within the Design Parameters sheet, the user can change the default parameters for sizing, such as EVA time and metabolic rate capacity, and modify parameters relevant to the heat balance, such as environmental conditions or suit parameters. System cooling requirements are calculated in GUS using a heat balance, with contributions from crew metabolic heat, PLSS equipment heat generation, and environmental heat loss/gain. Convective heat transfer calculations are included for Martian environments, which are not applicable in Lunar, station, and deep space settings.

The GUS tool was programmed to include a majority of the technologies identified at the start of the project, many of which were modeled in a previous PLSS sizing tool.[11] Of the technologies included from the previous tool, many were upgraded within GUS to improve accuracy and reflect advancements from more current research findings. A total of 23 of the technologies included in GUS had not been modeled prior to this study.[9] Mass balances for new technologies were performed using experimental sizing data found in literature and was correlated to PLSS operational requirements when necessary. In many cases, it was also necessary to implement sizing parameters that changed with PLSS operating conditions.

E. Schematic Identification & Analysis Process

Following initial technology elimination, an efficient method was developed to narrow down technologies further via an equivalent system mass (ESM) analysis. Schematic combinations were then compiled from the reduced technology list. Finally, unique schematics were selected for further evaluation by combining the technologies in each major function with the lowest ESM. The ESM analysis process is detailed below.

1. Equivalent System Mass of Technologies

ESM takes disparate sizing characteristics and converts them into a unified, quantifiable metric that can be easily compared among multiple candidates. Equivalency factors are applied to convert parameters such as volume and power into units of mass. These converted values are then added to the actual system mass to yield a total ESM value. This method of analysis is typically used in life support applications to assess vehicle-level impacts of equipment. Since the PLSS is a complete life support system, an ESM analysis is not necessary for an entire schematic. Therefore, ESM analyses were performed on a technology-by-technology basis as a preliminary means to narrow down the technology list by comparing technologies within each function, using the xPLSS as a baseline. By accounting for performance characteristics on a technology level with an ESM analysis, a parallel comparison of PLSS technology options is achieved, thereby allowing the most realistic options with respect to their impacts on the entire PLSS mass to be determined. This method therefore allows for the creation of a more concise list of options for each function of the Martian PLSS, as opposed to evaluating thousands of possible combinations. Vehicle-level impacts were not included in the ESM analysis, as it was only used to narrow down technology options based on PLSS mass. The ESM equation used for this analysis, as well as a table describing its variables (Table 2), is provided below for reference.[12]

$$\mathbf{ESM} = \mathrm{M_S} + \gamma_{\mathrm{O2}}\mathrm{M_{O2}} + \gamma_{\mathrm{H2O}}\mathrm{M_{H2O}} + \gamma_{\mathrm{V}}\mathrm{V_S} + \gamma_{\mathrm{P}}\mathrm{P_S} \qquad (1)$$

Table 2. ESM variables.

Variable	Description	Units
M_s	System mass: dry + fluid + O_2, H_2, H_2O, misc. consumables	kg
M_{O2}	Mass of O_2 consumed	kg
M_{H2O}	Mass of H_2O consumed or generated	kg
V_S	System volume	m^3
P_S	System power consumption	W-hr
γ	Equivalency factor	kg/x

In this analysis, power, volume, O_2 consumed, and H_2O consumed or generated by individual technologies were converted to equivalent mass values, as these four variables largely affect the sizing of the PLSS. If a technology consumes O_2, the mass of the O_2 is accounted for in the system mass, but the necessary increase in size of the O_2 tank is not. Therefore, the additional tank mass is accounted for in the O_2 consumed multiplied by its equivalency factor. The same is true for H_2O consumption and generation. Mass, power, volume, and consumables for each technology were calculated in the GUS tool by using the xPLSS schematic as a baseline.[13] This means xPLSS technologies were selected for every major function on the Schematic Evaluation sheet, outside of the subsystem technology being evaluated. When evaluating technologies for which CO_2 removal and H_2O removal were separate, the removal function not being evaluated was left blank since the RCA in the xPLSS accomplishes both functions. Once the appropriate schematic was selected, the GUS tool automatically computed the mass, power, volume, and consumables quantities for the technology being evaluated, which were then plugged into Equation 1. The equivalency factors shown in Equation 1 were calculated using data from the xPLSS (e.g., the volume equivalency factor was calculated by dividing the xPLSS system mass by the xPLSS system volume). Calculated values for these equivalency factors are provided in Table 3. It is important to note that a more accurate method for this ESM evaluation would have been to use the mass of the PLSS structure rather than that of the entire PLSS when calculating equivalency factors, as the method utilized can lead to over or underprediction of a technology's mass impact. However, based on the spread of the technology masses observed in this assessment, it is unlikely that updating the equivalency factors would have resulted in a different outcome. Nonetheless, this will be taken into consideration in future work.

Table 3. Equivalency factors used in technology ESM analysis.

Equivalency Factors	Description	Value
γ_{O2}	xPLSS O_2 tank dry mass/ O_2 fluid mass	2.46 kg/kg
γ_{H2O}	xPLSS H_2O tank dry mass/ H_2O fluid mass	0.14 kg/kg
γ_{V}	xPLSS system mass/xPLSS system volume	747.48 kg/m^3
γ_{P}	xPLSS system mass/xEMUpower consum.	0.10 kg/W-hr

Once ESMs were calculated for each technology, the highest ESM technologies in each major function category were eliminated. At this stage, additional technologies were also eliminated if they were deemed incompatible with the Martian environment, either by not meeting system cooling requirements or necessitating environmental conditions not applicable on Mars (e.g., vacuum). There were two exceptions to this rule; the lithium chloride absorber radiator (LCAR)[14,15] and variable emissivity electrochromic (VE EC) radiator[16]. These two thermal control technologies could meet system cooling requirements if equiped with an additional topping unit (such as a phase change material (PCM) or SWME). The low ESMs of these thermal control technologies in combination with topping units allowed these technologies to continue forward in the study. In total, 13 technologies were eliminated from the list during the ESM analysis stage, leaving 44 to be considered for schematic evaluations.

2. Schematic Combinatorial Process

The technologies that remained after the technology-level ESM analysis were combined into schematics. For this study, a schematic consists of the eight major functions of the PLSS, plus packaging and some baseline emergency backup functions. A python script was developed that allowed for efficient bulk computation of every single schematic combination that could be compiled from the down-selected technology list, with a few constraints implemented to restrict technology pairings when appropriate (e.g., the cryogenic scrubber for CO_2 removal can only be paired with liquid O_2 (LOX) for O_2 storage and supply). The schematic options produced were then reviewed and manually filtered based on technology compatibility across each major function, total system mass, and uniqueness. Schematics containing unfavorable technology combinations were eliminated. For example, it was determined a LOX/cryogenic scrubber pair would not perform well with the evaporative cooling and ventilation garment (ECVG) due to its immediate removal of metabolic heat and subsequent increase in the power supply needed for LOX vaporization.

From the reduced technology list, schematics containing the lowest total system mass were selected for further evaluation. As an initial guess for total system mass, the total ESM of each schematic was computed by taking the sum of the ESMs for each technology comprising the architecture. While computing total PLSS mass is a more appropriate and robust method, the use of a total ESM allowed for thousands of schematic combinations to be sorted within the time constraints of the study. A GUS evaluation of all possible schematic combinations to confirm the lowest mass options is intended as future work.

Unique combinations of technologies were also prioritized in this study. In most cases, if the suggested schematics were identical in all but one subsystem, only the lowest ESM option was considered. An exception to this rule was made when considering CO_2 removal, humidity removal, and thermal control. Since these three functions in the xPLSS would not work on Mars as they currently operate, it was advantageous to further evaluate low ESM schematics that had unique technologies in just one of these three categories. With the conclusion of this analysis process, seven schematics were identified and selected for further assessment.

III. Selected mxPLSS Schematics

The seven schematics selected for evaluation in GUS are detailed in this section. For each schematic, the technologies chosen for each PLSS major function are listed, along with emergency backup functions for O_2 storage and supply, thermal control, thermal loop drive, and power supply. Emergency backup technologies for the listed functions remain consistent across every schematic and are based on the xPLSS, with the exception of O_2 storage and supply, which has two variations depending on whether the primary tank is LOX or GOX.

A. Schematic 1

The first schematic recommendation (Figure 3) pairs LOX for O_2 storage and supply with a dual cryogenic scrubber for

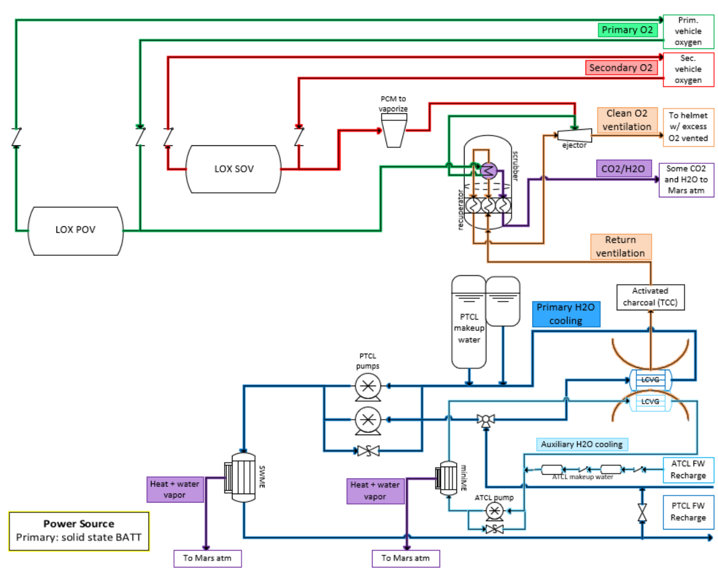

Figure 3. Schematic 1.

CO_2 and humidity removal. An ejector is chosen as the ventilation flow drive and a pump (+backup pump) is used for the thermal loop drive. An upsized SWME is selected for thermal control, activated charcoal for trace contaminant control, and a solid-state battery for power supply. The emergency backup functions consist of a secondary LOX tank with a PCM vaporization unit, a small SWME (i.e., miniME) for backup thermal control, an additional pump to drive the flow, and a Li-ion battery for backup power supply.

Major considerations for schematic 1 include the following: The ejector is chosen over the fan because the increased O_2 flowrate required by the dual cryogenic scrubber meets or exceeds the flowrate required by the ejector. The cryogenic scrubber is assumed to only partially regenerate during an EVA. Therefore, it requires maintenance post EVA to remove any remaining frozen H_2O and/or CO_2. In order to meet performance requirements in the Martian atmosphere, the upsized SWME has been modified to have additional hollow fiber cartridges, resulting in an increase in mass that is variable with respect to the operational environment (see Table 5). LOX would have to be resupplied at the vehicle level. The backup O_2 storage and supply technology includes a PCM vaporization unit to vaporize the secondary LOX tank if needed. The primary LOX tank is vaporized in the cryogenic scrubber (Figure 3). The solid-state battery chosen is a newer technology that has a specific energy estimated at triple that of conventional li-ion batteries,[17] making it a highly promising power supply option.

B. Schematic 2

The second schematic recommendation (Figure 4) is similar to the first in that it pairs LOX for O_2 storage and supply with a cryogenic scrubber. However, the cryogenic scrubber is only used for CO_2 removal and a condensing heat exchanger (CHXR) is chosen for humidity removal. The remaining primary functions and emergency backup functions are identical to schematic 1.

Major considerations for schematic 2 include the following: The ejector is again chosen over the fan because the increased O_2 flowrate required by the cryogenic scrubber meets or exceeds the flowrate required by the ejector. The stand-alone CO_2 removal cryogenic scrubber has been sized identically to the dual cryogenic scrubber since it is assumed to partially regenerate throughout an EVA. However, the cryogenic scrubber still requires maintenance post EVA to remove any remaining frozen CO_2 that could not be regenerated during an EVA. It is assumed that the H_2O condensed by the CHXR is directed to the H_2O tank, which reduces the required tank volume and H_2O consumables, thereby offsetting more than half of the added mass from the CHXR unit. Considerations for LOX, backup O_2, the solid-state battery and upsized SWME are the same as those listed for schematic 1.

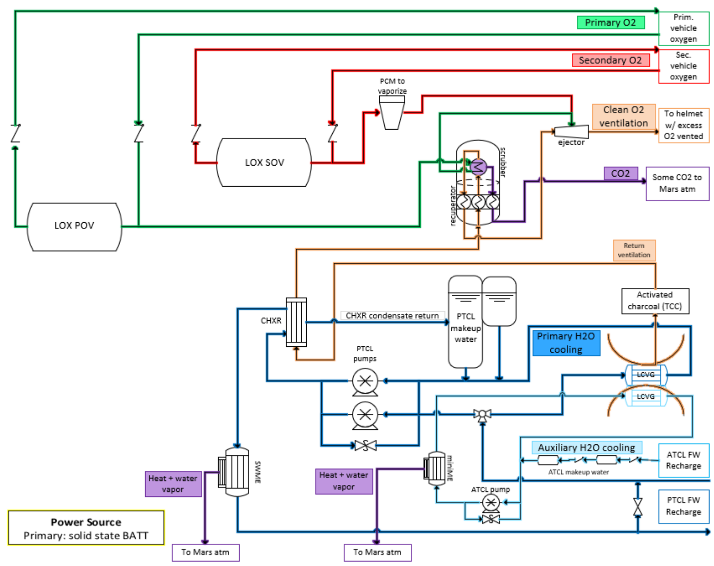

Figure 4. Schematic 2.

C. Schematic 3

The third schematic recommendation (Figure 5) closely resembles the xPLSS architecture but has been modified for operation on Mars. GOX is paired with a fan to supply O_2 and ventilation flow drive, while an LCVG is paired with a pump and upsized SWME to provide thermal control and thermal loop drive. An RCA modified with a sweep gas (O_2 blown across the bed during venting) is used for CO_2 and humidity removal. For trace contaminant control, nanoporous silica has been chosen over activated charcoal, and the power supply selected is again a solid-state battery. Since schematic 3 uses GOX as the primary O_2 supply, a secondary GOX tank is listed with a regulator as the O_2 and storage supply emergency backup function. Backup thermal control, thermal flow drive and the power supply functions remain identical to the first two schematics.

Major considerations for schematic 3 include the following: Nanoporous silica is chosen over activated charcoal because it is vacuum-regenerable[18] and can meet low mass requirements if integrated within the RCA. Here an assumption has been made that through integration with the RCA, metabolic H_2O can be used for operation of the nanoporous silica technology rather than sizing up the H_2O tank and increasing consumables. O_2 is used as the sweep gas for the RCA and it is assumed that O_2 from the main vent line can be diverted to the RCA at a standard flowrate of 6 acfm. These operational conditions are assumed to be sufficient to allow the RCA to perform effectively on Mars and without the need for additional fans or pumps. Considerations for the solid-state battery and upsized SWME are the same as those listed for schematic 1.

D. Schematic 4

Schematic 4 (Figure 6) is identical to schematic 3, with the exception of the thermal control technology. GOX is again paired with a fan for O_2 supply and ventilation flow drive. An LCVG is paired with a pump for thermal loop drive, but the thermal control unit is now a VE EC radiator with a SWME implemented as a topping unit/backup function. An RCA with a sweep gas is still used for CO_2 and humidity removal, nanoporous silica is still used for trace contaminant control, and a solid-state battery is again selected for the power supply. The emergency backup functions are identical to schematic 3.

Major considerations for schematic 4 include the following: The VE EC radiator/SWME is chosen over the upsized SWME alone because venting of water by use of the SWME is only necessary when system cooling requirements cannot be fully met by the VE EC radiator, thus conserving H_2O. This could be a better option depending on Mars environmental conditions and how much surface area can be occupied by radiator panels. The sizing calculations for the SWME attachment assume it rejects excess heat based on maximum metabolic rates sustained over an 8-hour EVA. A transient analysis of this technology would produce a more accurate mass estimate. Even though the emissivity of the radiator is set to increase or decrease depending on heat rejection needs, the radiator would need to be freeze tolerant. Considerations for the nanoporous silica, RCA, and solid-state battery are the same as those listed for schematic 3.

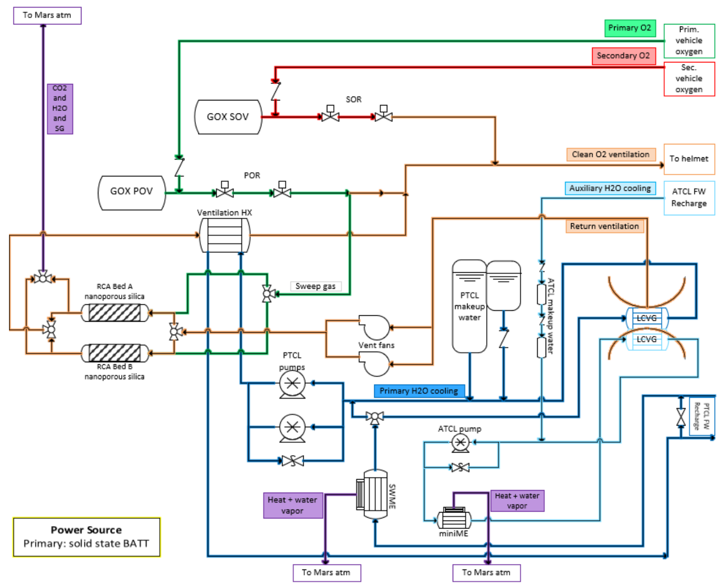

Figure 5. Schematic 3.

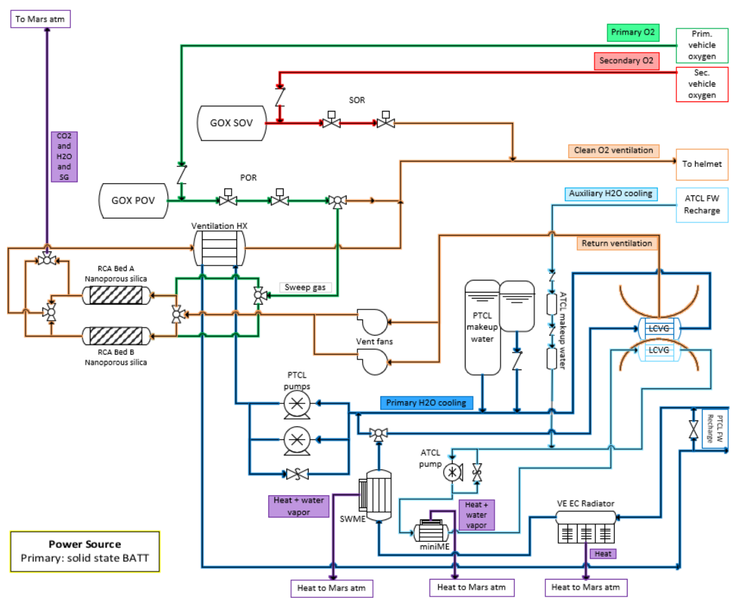

Figure 6. Schematic 4.

E. Schematic 5

The fifth schematic recommendation (Figure 7) is more unique than the previous schematics in that it employs newer technologies that have not previously been implemented into a PLSS. While GOX is still paired with a fan to supply O_2 and ventilation flow drive, the LCVG is replaced with an ECVG[15] and is paired with an LCAR and PCM topping unit to provide thermal control. Thermal loop flow drive is performed by a pump. Humidity and CO_2 removal are performed by an RCA with O_2 sweep gas, RCA-integrated nanoporous silica is used for trace contaminant control, and a solid-state battery supplies power. The emergency backup functions remain consistent with schematic 3 and 4.

Major considerations for schematic 5 include the following: The LCAR is the primary cooling unit in the system, but it is not capable of meeting the cooling demands that have been calculated and defined across the full range of standard metabolic rates under certain Martian environmental conditions (nominal and hot). In such cases, a sub-cooled PCM is implemented as a topping unit to the LCAR. This technology would need to be subcooled prior to EVAs in warmer environments, contributing to greater impacts at the vehicle-level. The sizing calculations for the PCM topping unit assume it rejects excess heat based on maximum metabolic rates sustained over an 8-hour EVA. A transient analysis of this technology would produce a more accurate mass estimate. The ECVG/LCAR may be capable of collecting and removing metabolic H_2O from the vent loop, but this schematic assumes the RCA is used for humidity removal. Considerations for the nanoporous silica, RCA, and solid-state battery are the same as those listed for schematic 3 and 4.

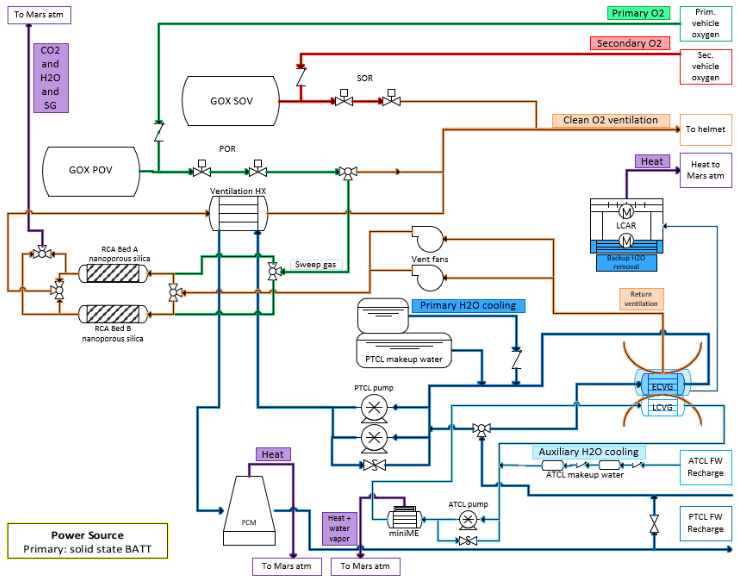

Figure 8. Schematic 5.

F. Schematic 6

The sixth schematic recommendation (Figure 8) is the most complex recommendation since one technology performs three functions. O_2 storage and supply is performed by GOX with a fan for flow drive. An LCVG with a pump is used for the ventilation and thermal loop network and flow drive. Trace contaminant control is performed with activated charcoal and power is supplied by a solid-state battery. CO_2 removal, humidity removal, and thermal control are all performed using metabolic heat regenerated temperature swing adsorption (MTSA).[19] The MTSA utilizes seven different heat exchangers to remove metabolic heat and CO_2/humidity, by strategically interfacing the ventilation loop, thermal loop, and a liquid CO_2 loop with temperature swing adsorbent beds. The emergency backup functions remain consistent with schematic 3, 4, and 5.

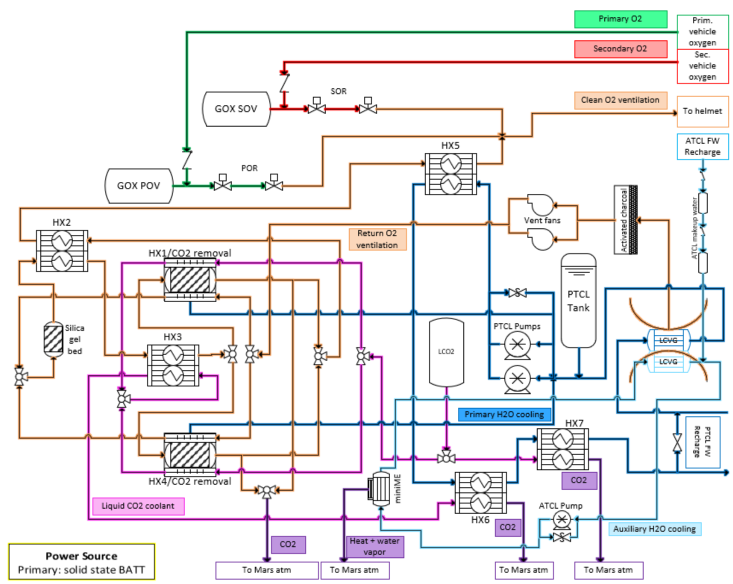

Figure 7. Schematic 6.

Major considerations for schematic 6 include the following: MTSA performs three functions efficiently, but if an issue arises in one, all three of those functions will be negatively affected. Redundant systems should be carefully designed and implemented to support the necessary functions should an issue arise with the primary MTSA system. Since the driving force behind the MTSA swing beds is metabolic heat, heat leaks to the environment need to be minimized. The MTSA technology employs the use of a liquid CO_2 coolant, which is consumed over the course of an EVA and would need to be replenished. The Mars atmosphere could be considered as the source of CO_2.

G. Schematic 7

The seventh schematic recommendation (Figure 9) closely resembles the architecture of the xEMU with modifications for operation on the Martian surface. O_2 storage and supply is performed by GOX with a fan for flow drive. An LCVG with a pump is used for the ventilation and thermal loop network and flow drive. Both CO_2 removal and trace contaminant control are performed with a metal oxide (MetOX) unit. Humidity removal is covered by a condensing vent-liquid heat exchanger. Thermal control is performed with a sub-cooled PCM, and power is supplied by a solid-state battery. The emergency backup functions remain consistent with schematic 3, 4, 5, and 6.

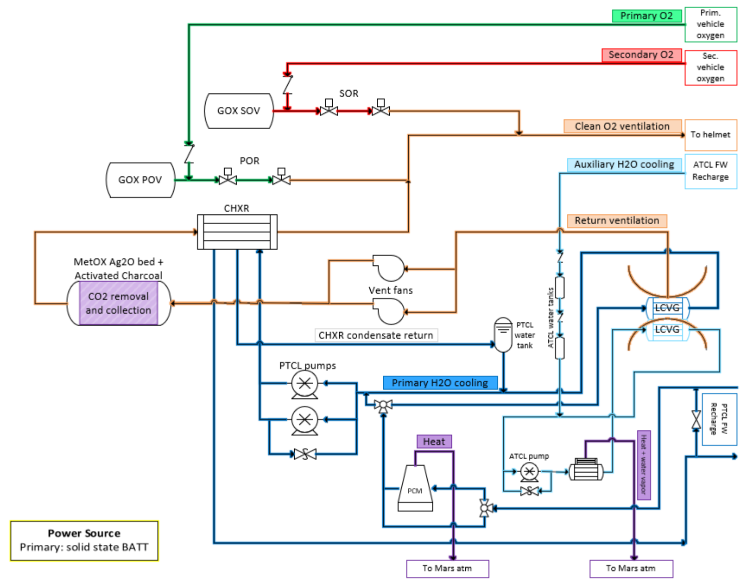

Figure 9. Schematic 7.

Major considerations for schematic 7 include the following: The MetOX unit contains activated charcoal so a stand-alone trace contaminant control (TCC) technology is not needed. MetOX requires regeneration post-EVA, which will have greater impacts at the vehicle-level. The sub-cooled PCM would need to be cooled prior to each EVA, which would have greater impacts at the vehicle-level. The sizable mass of the PCM technology is more than other thermal control technologies and will increase when evaluated under warmer conditions than Mars nominal. It is assumed that the metabolic H_2O condensed by the CHXR is directed to the primary thermal control loop H_2O tank.

IV. Assessment and Final Schematic Recommendations

After initial evaluation of the seven selected schematics, a more detailed assessment of each option was executed using the GUS tool. System-level effects, not currently incorporated into GUS, were separately considered and are discussed in this section. Given that many of the mxPLSS technologies identified are dependent on the vehicle architecture, three of the seven mxPLSS schematics were ultimately recommended to provide options based on the final vehicle architecture adopted for Mars missions. To arrive at these final recommendations, schematics were assessed relative to one another, with an emphasis on a direct comparison between similar schematics. Mass, power, volume, and consumables requirements under Mars nominal conditions were computed for each schematic, and additional mass-focused analyses were conducted to compare similar schematics in all three Martian environments (cold, nominal, hot). The subjective aspects not captured by the GUS tool, including maintainability, operability, and multi-mission use, were qualitatively compared. Certain subjective criteria were simply commented on due to limited information at this time (e.g., vehicle demands) or were found to not differ significantly between schematics (e.g., safety).

A. Initial Rankings from GUS Evaluation

All seven schematics' total mass, volume, power consumption, H_2O consumption, and O_2 consumption were computed for a Mars nominal EVA conducted over 8 hours. Average and maximum metabolic rates were assumed to be 350 W (1194 BTU/hr) and 530 W (1810 BTU/hr), respectively. The maximum metabolic rate was used to size the dry mass of thermal control technologies or technology components whose heat rejection capabilities are directly dependent on their size (e.g., radiators and SWME cartridges), while the average metabolic rate was used to size component properties that are adjustable to fluctuating operating conditions at a fixed unit size (e.g., SWME H_2O consumed and sub-cooled PCM). Suit pressure was set at 4.3 psia and inner suit temperature was taken as 294.3 K. Some technologies are expected to operate for longer than the 8-hr EVA duration due to the need for certain suit functions during EVA preparation and completion. In such cases, an equipment duration of 10 hours was used for component mass balances.

With an initial analysis under Mars nominal conditions, the schematics were ranked by total mass. Table 4 presents each schematic from lowest to highest mass, with their associated requirements for volume, power consumption, O_2 mass consumed, and H_2O mass consumed. The total mass of each schematic includes the mass of the primary technologies that satisfy each major function, the mass of the emergency backup technologies, and an estimated packaging mass. Volume is calculated as the sum of the primary technology volumes and an estimated packaging volume. The mass and volume packaging factors were assumed to be the same as those for the xPLSS at values of 2.2 and 2.15, respectively. Consumables consist of the O_2 and H_2O resources that must be replenished each EVA.

Three schematic groupings can be identified from the schematic rankings table. There are two low mass options with LOX (schematics 1 and 2), two low mass options with GOX (schematics 3 and 4), and three higher mass options with GOX that require less consumables (schematics 5, 6, and 7). While the schematics within each grouping differ by more than what defines the grouping, these initial labels point to the vehicle architecture necessary for each mxPLSS schematic presented.

Table 4. Schematic rankings by mass in Mars nominal conditions, with associated volume, power consumption, and consumable mass.

Schematic	Mass (kg)	Volume (m3)	Power consumption (W-hr)	Consumables	
				O_2 (kg)	H_2O (kg)
1	87	0.047	266	8.6	3.5
2	88	0.046	266	8.6	2.9
3	98	0.046	419	1.7	3.7
4	98	0.044	422	1.7	3.2
6*	106	0.064	363	0.7	0.5
5	114	0.087	419	1.7	2.5
7	150	0.088	363	0.7	-

*consumes CO_2

B. Schematic Comparisons

Schematics within each grouping were evaluated under Mars hot and Mars cold environments for further comparison. Additional system-level subjective criteria were also considered at this stage of the assessment. The vehicle architectures that define the groupings are broadly stated as those which can provide LOX, those which can provide GOX, and those which can provide GOX but require a reduced amount of consumables per EVA.

1. *LOX Schematics*

Schematics 1 and 2 are the only selected schematics which require a vehicle that can supply the PLSS with LOX. These two LOX options have the lowest mass, require the least amount of power, and consume the most O_2 out of the seven schematics. Their low mass and power can primarily be attributed to the chosen CO_2 removal and ventilation flow drive technologies. The cryogenic scrubber has a significantly lower mass in comparison to the RCA + sweep gas, MTSA, and MetOX, and requires no power. The ejector also requires no power, which contrasts with the other five schematics that utilize a powered fan. Nevertheless, the cryogenic scrubber and LOX technologies consume a large amount of O_2. The flowrate requirements of the cryogenic scrubber and ejector are higher than the flowrate requirement for the helmet, resulting in O_2 lost to the environment. While not the highest, these two schematics also consume a significant amount of H_2O through the use of the SWME for thermal control. Therefore, the chosen vehicle architecture must be capable of supplying LOX and H_2O in relatively high quantities if schematic 1 or 2 is to become a viable mxPLSS schematic.

Relative to one another, the primary difference between schematic 1 and 2 is the technology chosen for humidity removal. While schematic 1 utilizes a dual cryogenic scrubber that accomplishes CO_2 and humidity removal, schematic 2 splits the functions, using a cryogenic scrubber only for CO_2 removal and a CHXR for humidity removal. The cryogenic scrubber is sized identically in both schematics since it is assumed to partially regenerate throughout an EVA. It is also assumed that the heat removed by the dual cryogenic scrubber is equivalent to the heat removed by the cryogenic scrubber and CHXR combo. The slightly higher mass of schematic 2 in all Mars environment cases (Table 5) is therefore attributed entirely to the CHXR. In this analysis, the CHXR directs condensed metabolic H_2O to the SWME tank which reduces the H_2O necessary for an EVA and decreases tank mass and volume requirements. In the Mars nominal case, directing the condensed H_2O decreases the total SWME mass (H_2O and tank mass) by ~0.8 kg, offsetting more than half the mass added to the system by the CHXR (1.3 kg) and saving ~0.6kg in H_2O lost to the environment (Table 4). This explains

Table 5. Mass comparison of LOX supplied schematics in Martian environments.

Environment	Mass (kg)	
	Schematic 1	Schematic 2
Mars Cold	85	86
Mars Nominal	87	88
Mars Hot	92	93

why the increase in mass upon addition of the CHXR is so small. Further investigation in to the cryogenic scrubber heat balance for combined CO_2 and H_2O removal versus CO_2 removal only is needed to determine whether there are positive thermal control benefits to using a CHXR that outweigh the slight increase in mass it adds to the system.

The two LOX supplied schematics do not differ from one another at a system-level aside from the amount of H_2O they consume. In either case, the cryogenic scrubber will need to be maintained after each EVA since it only partially regenerates throughout an EVA. The activated carbon used for trace contaminant control in both cases will also need to be replaced after some time since it is not regenerable. Therefore, since the mass of schematic 1 and schematic 2 do not differ significantly and schematic 2 consumes less H_2O, the reduced vehicle-level impacts of schematic 2 make it stand out as the more feasible LOX/cryogenic scrubber option.

2. GOX Schematics

Schematics 3 and 4 are the lowest mass schematics which require a vehicle to supply GOX instead of LOX. Relative to the LOX schematics, these two GOX architectures are ~10 kg higher in mass and consume more power, but consume significantly less O_2 (Table 4). The higher consumption of power can be attributed to the use of a fan for ventilation flow drive and the RCA + sweep gas (SG) for CO_2 and humidity removal. Compared to the other GOX schematic options (schematics 5-7), schematics 3 and 4 have a larger (or comparable) power consumption and consumables requirement, but lower system mass.

Compared to one another, schematic 3 and 4 only differ in the thermal control subsystem. While schematic 3 utilizes a SWME for thermal control, schematic 4 contains a VE EC radiator for primary thermal control and a SWME backup unit for warmer environments where the radiator cannot meet the system cooling requirements on its own. The amount of heat the VE EC radiator can reject is directly dependent on its heat transfer surface area. For the initial analysis, this value was set to 0.855 m^2 (approximately 75 percent of the xPLSS surface area). Sizing calculations for the SWME backup unit were executed under the condition of maximum metabolic rate capacity over the entire 8-hour EVA, which is an overprediction of the performance that would realistically be required. This overestimate with respect to SWME sizing still resulted in negligible mass differences between schematic 3 and 4 in Mars cold and nominal environments, and only a slight favorability towards schematic 3 (~1 kg) under the Mars hot condition (Table 6). Since the VE EC radiator does not consume any H_2O, the results suggest that the VE EC radiator/SWME combination (schematic 4) has the potential to be a better option, depending on environmental conditions and how much of the PLSS exterior can be occupied by radiator panels.

Table 6. Mass comparison of GOX supplied schematics that have consumables in Martian environments.

Environment	Mass (kg)	
	Schematic 3	Schematic 4
Mars Cold	93	93
Mars Nominal	98	98
Mars Hot	105	106

A brief additional analysis was conducted in GUS to better understand the VE EC radiator's heat rejection capabilities with increasing heat transfer surface area in different Mars environments (Table 7, Figure 10). Given that mission locations for EVAs on Mars have not yet been established, it is useful to look into how the PLSS may be optimized for different environmental conditions. In all cases, a backup SWME is still necessary to reach the maximum system cooling requirement but is not always necessary to reach the average system cooling requirement (Mars cold: 0.855 m^2 and above, Mars nominal: 1.05 m^2 and above). In Mars cold and nominal environments, an increase in the heat transfer surface area of the radiator results in a significant increase in heat rejection capability, which in turn decreases the necessary consumption of H_2O by the SWME. Under Mars hot conditions, the radiator is less efficient and would require more H_2O consumption by the SWME, but this warmer condition is a very conservative case (i.e., location specific and rare). Furthermore, to

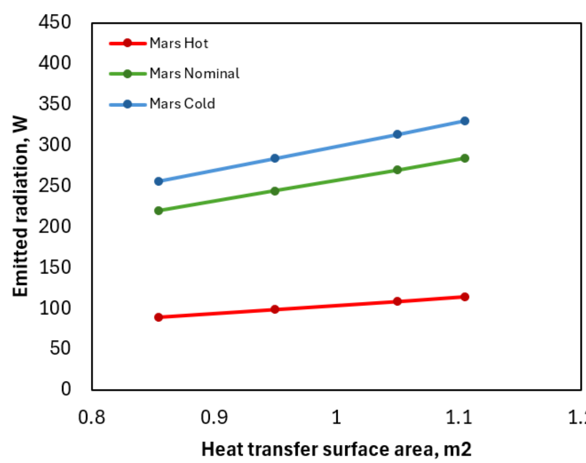

Figure 10. Emitted radiation vs heat transfer surface area for the VE EC radiator in Mars environmental conditions.

remain consistent, these results were recorded at an emissivity of 0.9; however, the emissivity of the VE EC radiator in the realistic application would be programmed to increase or decrease based on heat rejection needs.

Table 7. VE EC radiator heat rejection capability in Martian environments with different heat transfer surface areas.

Environment	System cooling requirement (W)		Heat rejection by VE EC radiator (W)			
	Average	Maximum	0.855 m^2	0.95 m^2	1.05 m^2	1.105 m^2 (entire PLSS)
Mars Hot	~320	~500	88	98	109	114
Mars Nominal	~270	~450	220	244	270	284
Mars Cold	~240	~420	255	284	313	330

At the system level, the primary difference between schematics 3 and 4 are their respective H_2O consumption criteria, which will depend on environmental conditions. In colder and nominal environments, the VE EC radiator may perform better than the SWME alone (so long as the radiator is freeze-tolerant). The non-thermal control technologies in both schematics are expected to be relatively low maintenance, comparable to that of the xPLSS. The nanoporous silica employed for trace contaminant control is regenerable and advantageous when considering the overall system-level effects. Given the mass similarities between the two schematics, and that the VE EC radiator/SWME combination is likely to have significant H_2O savings compared to the SWME alone, schematic 4 stands out as the most promising option for a vehicle architecture that can supply GOX.

3. Schematics with low consumables

The final three schematics consider a vehicle architecture where GOX is supplied but there is a need to reduce consumables. Schematics 5, 6, and 7 all have a combined H_2O and O_2 consumption that is low relative to the other four schematics (Table 4). These three options do, however, have the highest system masses and medium to high power consumption. However, outside of these broader similarities and unlike the previous two schematic comparisons, schematics 5–7 are very unique from one another.

Schematic 5 is similar to schematics 3 and 4 but utilizes an ECVG paired with the LCAR for thermal control. The ECVG and LCAR pair could potentially collect metabolic H_2O from the vent loop, but this schematic assumes an RCA + SG is used for CO_2 and humidity removal. Because the LCAR falls short of system cooling requirements at maximum metabolic rates in Mars nominal and hot environments, a sub-cooled PCM topping unit is also added for backup thermal control. Similar to the SWME backup unit, the PCM topping unit is sized based on the amount of excess heat it must reject under the conditions of maximum metabolic rate over the entire 8-hour EVA. Changes to the total system mass of schematic 5 in each environment are largely influenced by the degree to which the PCM topping unit is necessary for meeting system cooling requirements (Table 8). Under Mars cold conditions, the LCAR is capable of satisfying system cooling requirements on its own, resulting in a system mass comparable to schematic 6. This is not the case in the warmer Mars environments. In Mars hot and nominal conditions, the mass significantly increases due to the need for a larger PCM unit to accommodate the rejection of excess heat.

Table 8. Mass comparison of GOX supplied schematics that have reduced consumables in Martian environments.

Environment	Mass (kg)		
	Schematic 5	Schematic 6	Schematic 7
Mars Cold	106	103	146
Mars Nominal	114	106	150
Mars Hot	139	112	156

Schematic 6 is unique in that a single technology is used to satisfy CO_2 removal, humidity removal, and thermal control. The MTSA accomplishes these three functions efficiently with no power requirement and no H_2O or O_2 consumption. While the MTSA is a relatively high mass technology due to its complex equipment design,[9] the overall mass of schematic 6 is the lowest of the three options in all Mars environments (Table 8) because of its ability to perform three functions at once. This technology is promising but does require a few considerations. Heat losses would have to be minimized since the MTSA uses metabolic heat as the driving force for the CO_2 swing beds. It's also important to note that if an issue were to arise in one major function, all three PLSS functions performed by the MTSA could be negatively affected; therefore, backup functions would have to be chosen strategically. This technology also consumes liquid CO_2 as a coolant. In the Mars nominal environment, schematic 6 consumes 14.5 kg of CO_2, which would have to be supplied at the vehicle level. However, unlike O_2 and H_2O, there is a surplus of CO_2 in the Martian atmosphere, introducing the possibility for in-situ resource utilization (ISRU).

Schematic 7 closely resembles the xEMU PLSS. MetOX is used for CO_2 removal and a sub-cooled PCM operates in place of a sublimator for thermal control. A CHXR accomplishes humidity removal, and the remaining technologies are identical to schematic 6, except that the activated charcoal for trace contaminant control sits within the MetOX unit rather than being a standalone function. Schematic 7 requires the least number of consumables but has by far the highest system mass of the seven options evaluated in this study (Table 4). While the quantification of mass criteria for Mars missions is an ongoing assessment, i.e., a strict cutoff for maximum PLSS mass has not been established, the gravity conditions on Mars make the mass of the PLSS the primary factor to consider. Such a high mass for scematic 7 compared to the other options likely outweighs the benefit of consumables savings. For this reason, schematic 7 is not recommended further.

Unlike schematic 7, schematics 5 and 6 both contain CO_2 removal technologies, which are regenerable throughout an EVA. The nanoporous silica used for trace contaminant control on schematic 5 is also regenerable during an EVA, while the activated charcoal for schematic 6 would have to be replaced as it fills with CO_2. Therefore, schematic 5 would likely require the least amount of post-EVA maintenance out of these three vehicle-level options. Nevertheless, the potential for significant increases in on-back mass as a result of the PCM topping unit makes schematic 5 non-ideal as a PLSS architecture for EVAs conducted in warmer Martian environments. Therefore, since schematic 6 has the lowest mass and its main consumable could be harvested from Mars, schematic 6 stands out as the most promising option for a vehicle architecture that supplies GOX but requires a reduced number of consumables.

C. Final Results

Based on the assessment provided above, this study recommends three different schematics for the mxPLSS depending on the vehicle architecture chosen for Mars missions. These recommendations are summarized in Table 9. Note that in the preliminary schematic evaluation outlined in this work, only a rough manual estimation of system-level impacts was performed, and it was not assumed that EVAs would drive the vehicle decision on which technologies to include (e.g. LOX versus GOX). A more in depth assessment of system-level impacts using the GUS tool is a key recommendation for future work.

Table 9. Final mxPLSS schematic recommendations.

Functions	LOX Option: Schematic 2	GOX Option: Schematic 4	GOX & Reduced Consumables Option: Schematic 6
Oxygen storage and supply	LOX	GOX	GOX
Ventilation network	LCVG	LCVG	LCVG
Flow drive (ventilation & thermal loop)	Ejector + Pump	Fan + pump	Fan + pump
Carbon dioxide removal	Cryogenic scrubber	RCA + sweep gas	MTSA
Humidity removal	CHXR	RCA + sweep gas	MTSA
Thermal control	SWME	VE EC radiator + SWME	MTSA
Trace contaminant control	Activated charcoal	Nanoporous silica (RCA pair)	Activated charcoal
Power supply	Battery-solid state	Battery – solid state	Battery – solid state

V. Conclusion

A Mars EVA PLSS schematic study was conducted to provide guidance on Martian Exploration Portable Life Support System (mxPLSS) technology developments by investigating and identifying the most promising Martian PLSS architectures to date. Conducted from January 2024 to September 2024, a complete schematic study that culminated in three schematic recommendations for the mxPLSS was achieved. Beginning with a blank sheet approach, a comprehensive list of potential mxPLSS technoliges was compiled. The list was then narrowed down based on feedback from NASA, SMEs, collaborators, and a preliminary equivalent system mass (ESM) analysis under Mars nominal environmental conditions. Seven schematics with the lowest system mass were identified, and evaluation of each schematic was subsequently performed using a newly-developed PLSS sizing tool, the Guided Utility Sizer (GUS).

Throughout the execution and completion of this project, information gaps and areas for improvement were identified, some of which are noted here. Updates and additions to the GUS tool that will increase the sophistication, fidelity, and use-case of the tool should be carried out. For example, adding system level impacts would allow the tool to determine optimized architectures that minimize system resources for specific mission and multi-mission use cases. Additionally, the ESM method chosen to select low mass technologies could be improved or a rigorous approach could eliminate the need for utilizing ESM. While it is likely that the ESM method yielded the same conclusions as a more direct PLSS mass evaluation would have, it is recommended that a PLSS mass-based combinatorial scheme be conducted via GUS to verify the selected schematics in this study are indeed the lowest mass options. Future PLSS research is also recommended, particularly in the areas of restrictions to on-back mass and investigation of low/no TRL technologies, which could replace existing recommendations if further developed for space applications.

Acknowledgments

This project acknowledges funding from the Mars Campaign Office. The authors also gratefully acknowledge the entire NASA PLSS team at Johnson Space Center for their input throughout the project.

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