

Mars Exploration Portable Life Support System Schematic Study: Architecture Down-Selection

Madeleine C. Oliver, Ph.D.¹, Emma J. Quick², Dana M. Masangkay, Ph.D.³,
Isabella M. LeJeune-Bolivar⁴, Lawrence W. Barrett, Ph.D.⁵, and Bruce C. Conger⁶
Amentum, Houston, Texas, 77058

Noah L. Andersen⁷
HX5, LLC, 2224 Bay Area Blvd, Houston, TX, 77058

Cinda Chullen⁸, Colin Campbell⁹, and Ryan Ogilvie¹⁰
NASA Johnson Space Center, Houston, TX, 77058

Previous NASA Portable Life Support System (PLSS) designs have been focused on assisting extravehicular activity (EVA) in low gravity, vacuum environments. Development of a Mars Exploration Portable Life Support System (MxPLSS) therefore requires modifications to the baseline PLSS design that accommodate the unique operational conditions characterizing EVAs on Mars. In our previous study presented at the International Conference on Environmental Systems (ICES) 2025, paper number ICES-2025-90, a blank sheet approach pinpointed technologies with the potential to satisfy each major function of the MxPLSS. A comprehensive list of equipment was compiled, combinations of technologies were evaluated and compared, and seven promising schematics were recommended. Out of that study came a newly developed PLSS sizing tool, the Guided Utility Sizer (GUS), which aided in the comparison and detailed assessment of proposed architectures. As a continuation of this effort, enhancements to the GUS tool were made with the goal of confirming the most feasible schematic to develop into a workable test stand. Broadening and refinement of the tool's capabilities were carried out to allow for more sophisticated insight into technology impacts at the PLSS- and vehicle-level. With the help of an improved down-selection process, thousands of technology combinations were evaluated and compared in the upgraded tool, and higher-quality schematic recommendations were made. This paper summarizes the study approach, schematic selection process, and final assessment that culminated in recommendations for open loop, semi-open loop, and closed loop PLSS configurations optimized for nominal Martian environmental conditions at EVA durations of 2, 4, 6, and 8 hours.

Acronyms and Nomenclature

ATCL	=	auxiliary thermal control loop	MxEMU	=	Mars Exploration Extravehicular
BATT	=	battery			Mobility Unit
BC	=	boost compressor	O ₂	=	oxygen

¹ Chemical Engineer – Modeling & Simulation, Thermal & Life Support Systems Analysis, JETSII.

² Chemical Engineer – Modeling & Simulation, Thermal & Life Support Systems Analysis, JETSII.

³ Thermal Analysis Engineer, Thermal & Life Support Systems Analysis, JETSII.

⁴ Chemical Engineer Intern, Thermal & Life Support Systems Analysis, JETSII.

⁵ Chief Engineer, Thermal & Life Support Systems Analysis, JETSII.

⁶ Senior Subject Matter Expert, Thermal & Life Support Systems Analysis, JETSII.

⁷ Thermal Analysis Engineer, Thermal & Life Support Systems Analysis, JETSII.

⁸ Mars Campaign Office Spacesuit Portfolio Lead, Space Suit and Crew Survival Systems Branch, EC5.

⁹ EVA Technical Discipline Lead, Space Suit and Crew Survival Systems Branch, EC5.

¹⁰ Mars PLSS Project Lead, Space Suit and Crew Survival Systems Branch, EC5.

Trade names and trademarks and company names are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

CHXR	=	condensing heat exchanger	PCM	=	phase change material
CO ₂	=	carbon dioxide	PLSS	=	Portable Life Support System
CSSE	=	Constellation Space Suit Element	POR	=	primary oxygen regulator
EMU	=	Extravehicular Mobility Unit	POV	=	primary oxygen vessel
ESM	=	equivalent system mass	PTCL	=	primary thermal control loop
EVA	=	extravehicular activity	RCA	=	rapid cycle amine
FW	=	feedwater	SG	=	sweep gas
FY	=	fiscal year	SOR	=	secondary oxygen regulator
GOX	=	gaseous oxygen	SOV	=	secondary oxygen vessel
GUS	=	Guided Utility Sizer	SWME	=	spacesuit water membrane evaporator
HFM	=	hollow fiber membrane	TCC	=	trace contaminant control
H ₂ O	=	water	TRL	=	technology readiness level
HP	=	heat pump	VBA	=	Visual Basic for Applications
HX	=	heat exchanger	VE EC	=	variable emissivity electrochromic
LCVG	=	liquid cooling ventilation garment	xEMU	=	Exploration Extravehicular Mobility Unit
Li-ion	=	lithium-ion	xPLSS	=	Exploration Portable Life Support System
LiOH	=	lithium hydroxide			
LOX	=	liquid oxygen			
MAIT	=	Mission Analysis and Integration Tool			
MxPLSS	=	Mars Exploration Portable Life Support System			

I. Introduction

THE Mars environment poses unique challenges for PLSS technologies that necessitate modifications to the NASA baseline exploration PLSS (xPLSS) design. Some of the major challenges regarding extravehicular activities (EVAs) on Mars include the following:

- Low atmospheric pressure of ~0.15 psia
- Gaseous atmosphere with a composition of 95% carbon dioxide
- Storms and seasonal weather changes
- Mass restrictions due to 0.38 g gravity

These obstacles call for a Mars xPLSS (MxPLSS) architecture that does not rely on venting to vacuum, maintains reliability in dynamic conditions, and is optimized for mass and volume by incorporating characteristics like regenerability. Schematic studies such as those for the Space Shuttle program, the Apollo program, and the most recent Constellation Space Suit Element (CSSE) [1] have historically been used to accomplish this type of curated PLSS design and have provided guidelines for the MxPLSS roadmap [2]. In congruence with the NASA Moon to Mars [3] timeline, the Mars Schematic Study was conducted over fiscal year (FY) 2024 and 2025 to direct the MxPLSS prototype design and fabrication expected to begin in FY26.

In the initial FY24 Mars Schematic Study (detailed in ICES-2025-90 [4]), a blank-sheet approach was carried out to compile a list of promising technologies that could satisfy one or more of the eight major functions of the PLSS: oxygen storage and supply, ventilation network, ventilation and thermal loop flow drive, carbon dioxide removal, humidity removal, thermal control, trace contaminant control, and power/energy storage. Out of that study came the Guided Utility Sizer (GUS) Excel tool [5] for assessment and comparison of PLSS architectures, which was successfully used to narrow down and evaluate proposed MxPLSS schematics. While the schematic analysis was insightful, it had limitations related to simplifications made in the initial version of GUS. The focus of the FY25 study was thus to improve and enhance the capabilities of the GUS tool to maintain alignment with the state-of-the-art as well as increase its fidelity for schematic assessment. From April 2025 to September 2025, improvements to GUS were implemented, and a higher-fidelity down-selection process was subsequently conducted using revised performance, mass efficiency, and reliability considerations. This paper summarizes the study approach, schematic selection process, and final assessment that culminated in refined MxPLSS schematic recommendations for open loop, semi-open loop, and closed loop PLSS configurations. Schematics were evaluated under Mars nominal environmental conditions and compared based on PLSS- and vehicle-level sizing metrics at 2-, 4-, 6-, and 8-hour EVA times.

II. Study Approach

In FY25, enhancements to the GUS tool were made with the goal of confirming the most feasible schematic to develop into a workable test stand. Expansion and refinement of the tool's capabilities were carried out to allow for more sophisticated insight into technology impacts at the PLSS- and vehicle-level. With the help of an improved down-selection process, thousands of technology combinations were evaluated and compared in the upgraded tool, and higher-quality schematic recommendations were made.

A. GUS Upgrades

At the conclusion of the FY24 study, the GUS tool only had the capability to evaluate mass, volume, power, and consumables quantities for primary subsystem PLSS technologies. The tool did not consider contributions from additional utilities such as regulators, ventilation heat exchangers, or back up flow drive components, and it did not consider mass, volume, power, and consumables quantities for secondary subsystems. In addition to this, the tool did not evaluate the system-level impacts of selected schematics, such as any additional vehicle capabilities that may be necessary to support a given PLSS technology. Furthermore, thermal control capabilities for selected schematics were only capable of being evaluated under steady state conditions, with fixed metabolic rate and environmental parameters being assumed over the course of an entire EVA. To enhance the fidelity of EVA evaluations and overall viability of schematics, the following major upgrades to GUS were made:

- Addition of the hollow fiber membrane technology for carbon dioxide and humidity removal, and modifications to previously existing technologies to maintain relevancy to the state of the art
- Addition of secondary subsystem sizing (treated as open loop) as well as an option to specify open or closed loop primary subsystem configurations
- Habitat/lander mass and architecture penalties for system-level assessment of schematics, including pre- and post-EVA consumables calculations
- Enablement of transient heat balance analyses for selected PLSS schematics to increase fidelity of EVA evaluations in various environments
- Improved tailoring to Mars missions via addition of location-specific Mars environments (not utilized in this study)

With these improvements, the schematic analyses presented in this work incorporated both primary and secondary subsystem contributions, as well as system-level assessments of technology impacts on the vehicle level. Different system architectures could be investigated at different EVA times, and transient analyses allowed for better insight into technology capabilities and limits. Detailed information on all upgrades made to GUS can be found in the Mars Schematic Study FY25 final report [6]. Additional information on the GUS tool can be found in the GUS User's Guide [7].

B. Schematic Evaluation

For schematic down-selection in the FY24 study, an equivalent system mass (ESM) approach was used to narrow down technologies based on their individual masses, and the lowest mass options for each major function were paired together and evaluated in GUS. A major goal of this FY25 study was to improve upon the fidelity of the previous down-selection process by using GUS to evaluate every possible schematic combination, rather than relying on ESM predictions for independent technologies. This was achieved with the help of the Mission Analysis and Integration Tool (MAIT) [8], a MATLAB and Simulink program that combines modular subsystem sizing models to conduct parametric studies on model inputs. Given a list of input and output variables, MAIT worked in conjunction with the GUS tool by automatically plugging in technology options for each PLSS major function and extracting calculated sizing and performance parameters for the combined schematic. The tool was able to cycle through thousands of schematics at different EVA times, and the results were sorted and postprocessed to determine the lowest PLSS and vehicle mass options for open and closed loop configurations at each EVA duration. To minimize run times for MAIT processing, constraints were implemented that allowed the program to skip through incompatible or redundant schematic pairings. Certain assumptions were also made concerning likely MxPLSS requirements, including an estimated PLSS mass goal of < 62 kg [6], [9].

The average and maximum metabolic rates for schematic evaluations were assumed to be 350 W (1194 BTU/hr) and 530 W (1810 BTU/hr), respectively, for the primary subsystem and 295 W (1007 BTU/hr) and 350 W (1194 BTU/hr), respectively, for the secondary subsystem. These values were predicted based on metabolic rate specifications for the xEMU [10]. The maximum metabolic rate is used to size the dry mass of thermal control

technologies or technology components in GUS whose heat rejection capabilities are directly dependent on their size (e.g., radiators, extra SWME cartridges), while the average metabolic rate is used to size component properties that are adjustable to fluctuating operating conditions at a fixed unit size (e.g. consumables). Suit pressure was set at 4.3 psia (nominal xEMU operating pressure) and inner suit temperature was set at 294.3 K (70 F). 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 close out. In such cases, an equipment duration defined by EVA time plus pre/post EVA time was used for component mass balances. Nominal EVA times were set between 2 and 8 hours with 0.5-to-1-hour durations for emergency operation. Pre- and post-EVA time was assumed to be 2 hours total per EVA. For the vehicle assessment, 2 hours of emergency EVA operation was assumed across the entire mission. Vehicle assessment calculations also assumed 2 crew members with a mission duration of 180 days. Number of EVAs was set to 100 scheduled plus 1 contingency, resulting in a recharge duration between EVAs of ~33 hours. For open loop scenarios, purge O₂ requirements were set to 2.2 lb/hr in the primary subsystem and 5.6 lb/hr in the secondary subsystem.

Relevant Mars environmental variables are detailed in Table 1 [11]. These values represent characteristic nominal and extreme conditions for Mars as a whole. For schematic down-selection, every schematic combination was evaluated under Mars nominal conditions. The vehicle assessment conducted in GUS for each schematic combination incorporates an ESM analysis in which Mars surface habitat infrastructure costs were considered, shown in Table 2 [12]. Additional default global and environmental variables can be found in the GUS tool [5]. Schematics were modeled in a steady state operation, assuming a fixed environment and fixed metabolic rate for the full duration of the EVA.

Table 1. Mars environmental properties.

Environment	Surface Temp (K)	Sky Temp (K)	Atm. Pressure (psia)	Wind Speed (m/s)	Solar Flux (W/m ²)
Mars Hot	299.8	139.8	0.145	20.12	173.5
Mars Nominal	212.0	139.8	0.124	10.05	110.4
Mars Cold	162.6	139.8	0.087	4.88	59.94

Table 2. Mars habitat infrastructure costs.

Habitat	Volume (kg/m ³)	Power (kg/kW)	Cooling (kg/kW)
Mars Surface	170	87	146

A mass packaging factor of 2.32 and a volume packaging factor of 2.62 were applied to all schematics to get total PLSS mass and volume. These packaging factors were estimated by taking the ratio of the total design verification test mass and volume of the xPLSS [13] to the total mass and volume of the xPLSS components modeled in GUS (such as the LCVG, RCA, SWME, and other major function technologies, whose mass balances do not account for any associated valves, sensors, or additional equipment other than those explicitly stated in Section III). For the xEMU, volume packaging was a bigger priority than mass packaging, which will not be the case for a Mars suit. More realistic estimates of packaging factors for Mars-specific applications may be closer to those for the Apollo PLSS, whose mass packaging factor is at a lower value of 1.6 [14]. Refined packaging factor estimates would improve schematic mass predictions and will be investigated in future work. Packaging factors were not applied for vehicle assessments.

III. Selected MxPLSS Schematics

With the upgrades to GUS in place, a parametric sweep analysis was performed that resulted in PLSS options optimized for open loop, semi-open loop, and closed loop primary subsystem configurations at 2-, 4-, 6-, and 8-hour EVA durations. The secondary subsystem configuration is always treated as open loop and is sized to operate for a duration of 0.5 hours with a 2-hour EVA and 1 hour with 4-, 6-, and 8-hour EVAs. For each case, the lowest mass options using both gaseous (GOX) and liquid (LOX) oxygen were recommended. A handful of architectures that optimize vehicle ESM were also considered.

Depending on the schematic, LOX in the primary subsystem may be modeled with a ventilation heat exchanger and heater for vaporization, whereas in the secondary subsystem, LOX is modeled in conjunction with a super ice phase change material (PCM) as a vaporizer. GOX in both the primary and secondary subsystems is modeled with a regulator. Ventilation loop flow drive is always a fan, unless there is already a large O₂ requirement upsizing the oxygen subsystem, in which case an ejector trades as a lower mass option. Secondary subsystems all use a sub-cooled PCM (super ice) for thermal control, unless the primary thermal control device is a radiator, in which case the radiator is assumed to be used for both primary and secondary thermal control (with extra tubing taken into consideration). The sub-cooled PCM is a consistently promising option for mass savings in the secondary subsystem, given that the

amount of phase change material is dependent on EVA duration, which is only 0.5-1 hour in the emergency scenarios investigated in this study. All recommended schematics use an LCVG for ventilation network, a pump for primary and secondary thermal loop flow drive, and a solid-state battery for primary and secondary power supply.

A. Open Loop

Open loop schematics are very simple. Given that the open loop PLSS architecture utilizes a purge valve to evacuate the ventilation loop containing CO_2 , humidity, and trace contaminants, the only major functions required for the PLSS are oxygen storage and supply, ventilation network, thermal loop flow drive, thermal control, and power supply. Ventilation returned from the LCVG is vented to the Mars atmosphere instead of scrubbed and recycled to the helmet. The pressure differential between the oxygen at the regulator and the Mars environment drives the flow through and out of the suit.

Figures 1 and 2 illustrate the open loop LOX and GOX schematic options for 2- and 4-hour EVA times, which feature a SWME + vacuum pump (VP) for thermal control. Schematics for the 6- and 8-hour EVA times are virtually identical but instead use the SWME upsized for Martian operation. The SWME + VP tends to trade better than the upsized SWME at shorter EVA times because the additional battery mass needed to accommodate the power requirement of the vacuum pump is less than the extra mass needed to achieve the system cooling requirement with a SWME alone. At longer EVA times, the additional battery mass outweighs the added mass to the upsized SWME.

Major considerations for these open-loop schematics include the following:

- The upsized SWME has been modified with additional hollow fiber cartridges to account for the Mars atmosphere. The number of cartridges vary with the environment/system cooling requirement.
- The SWME + VP is modeled in GUS based on several assumptions, one of which is a fixed power requirement of 75 W, which is likely an unconservative estimate. The mass balance for the SWME + VP in GUS has not yet been supported by experimental data.
- The mass of the sub-cooled PCM technology is very sensitive to environmental conditions and may not trade as well in warmer environments than Mars nominal.
- Open-loop systems may be subject to emissions regulations to ensure atmospheric safety of planet.

B. Semi-Open Loop

Semi-open loop architectures are more conservative than fully open loop systems but still allow for some venting of consumables from the ventilation loop to the surroundings. The trade-off is that fewer consumables need to be recharged prior to an EVA, but the PLSS may be heavier due to larger pieces of equipment such as ventilation scrubbing technologies and flow drivers. The different O_2 storage techniques for these schematics result in very

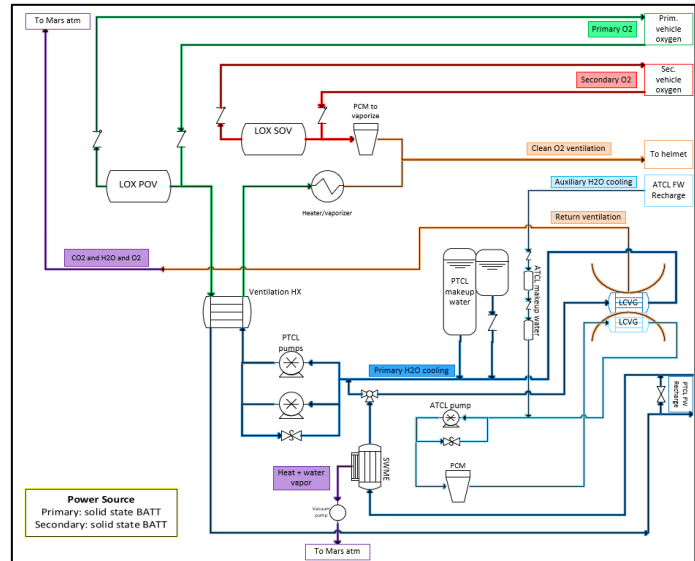


Figure 1. Open loop 2-, 4-hr EVA LOX schematic.

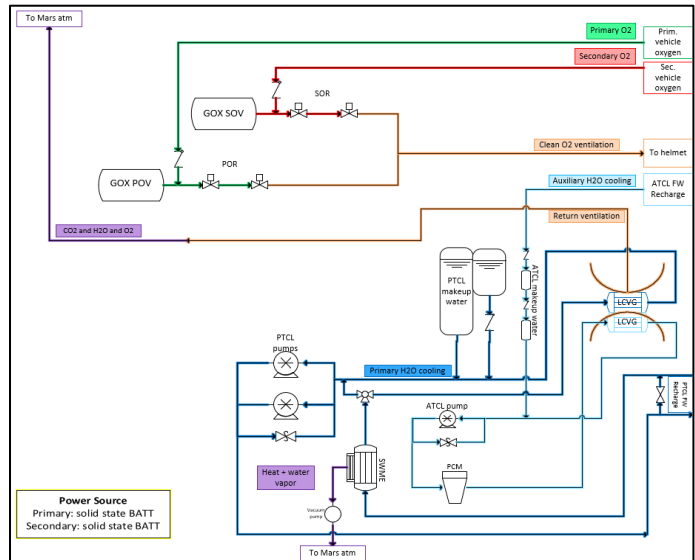
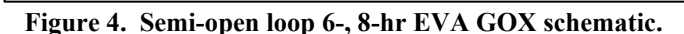
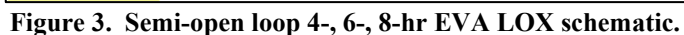


Figure 2. Open loop 2-, 4-hr EVA GOX schematic.

For semi-open loop LOX cases, the lowest mass schematics tend to favor a dual cryogenic scrubber for CO₂ and humidity removal and activated charcoal for TCC. The primary LOX supply in this case is vaporized in the cryogenic scrubber. Thermal control is handled by a SWME + VP for a 2 hour EVA versus a variable emissivity electrochromic (VE EC) radiator with a SWME attachment as a topping unit for 4, 6, and 8 hour EVAs. Figure 3 illustrates the semi-open loop LOX schematic using a VE EC radiator/SWME pair. The topping unit is necessary in warmer environments where the radiator cannot meet system cooling requirements on its own. This option trades better than the SWME by itself at longer EVA durations because water venting by use of the SWME is only necessary when cooling requirements cannot be fully met by the radiator, thus conserving H₂O. Still, environmental constraints of the radiator must be taken into consideration. When the VE EC radiator is used in the primary subsystem, the sub-cooled PCM typically utilized for thermal control in the secondary subsystem is now replaced by extra tubing that connects the secondary thermal loop to the primary radiator surface. In other words, the primary subsystem radiator is employed for both primary and secondary thermal control.

All the low mass semi-open loop schematics use an ejector for ventilation flow drive. An ejector is chosen over a fan because of the tradeoff between the low mass of the ejector itself and the added mass to the oxygen subsystem from the amount of O_2 it requires. The cryogenic scrubber and the RCA + SG both necessitate a flow rate of oxygen that meets or exceeds that required by the ejector, so extra O_2 tank mass is needed no matter what and the ejector in



turn trades as the lowest mass option. Major considerations for the recommended semi-open loop schematics include the following:

- The cryogenic scrubber is assumed to partially regenerate during an EVA, thus requiring maintenance post EVA to remove any remaining frozen water and/or carbon dioxide.
- The sizing calculations for the VE EC radiator and SWME attachment assume it rejects excess heat based on maximum metabolic rates sustained over the length of the given EVA duration. A transient analysis of this technology would produce a more accurate mass estimate.
- Even though the emissivity of the VE EC radiator is set to increase or decrease depending on the heat rejection needs, the radiator would need to be freeze tolerant.
- The sizing calculations for the VE EC radiator in the secondary subsystem assume it is 10% of the mass of the primary VE EC radiator. This assumption is intended to account for additional tubing that connects the secondary thermal loop to the radiator surface.
- For the RCA + SG, it is assumed that oxygen from the main vent line can be diverted to the RCA at the prescribed vent loop flow rate of 6 ACFM. These operational conditions are assumed to be sufficient to allow the RCA to perform effectively on Mars without the need for additional fans or pumps.
- Data from RCA tests under sweep gas or boost compressor operations was not available for the conditions of interest, and so several assumptions were made about the efficacy of these vacuum workarounds.

Considerations for the upsized SWME, SWME + VP, and sub-cooled PCM are the same as those listed for the open loop schematics.

C. Closed Loop

Closed loop architectures are the most resource-conservative option for life support systems. These systems tend to include heavier equipment that allow streams to be scrubbed and recycled with maximized efficiency. Venting to surroundings is kept to an absolute minimum; consumables are recycled as often as possible and metabolic waste products are kept on-board the suit to the extent possible until the equipment can either be recharged or replaced.

Closed loop LOX and GOX technologies are identical aside from their oxygen storage method. Thermal control is similar to many of the previously discussed cases, with the use of a SWME + VP or an upsized SWME depending on EVA time. A fan is used for ventilation flow drive, as oxygen venting is not desired. LiOH canisters (which contain activated charcoal) are used for CO₂ removal and TCC, but they do not take care of humidity, so a condensing heat exchanger (CHXR) is employed for H₂O removal. Separate technologies are used for CO₂ and H₂O removal because units like the CHXR can condense out water and recycle it back to the primary thermal control loop (PTCL), while LiOH canisters can scrub out and house CO₂ for the duration of the EVA. In the semi-open loop schematics, such tasks were accomplished with an RCA or a dual cryogenic scrubber, both of which vent products to surroundings.

Figures 5 and 6 illustrate the LOX and GOX schematics using a SWME + VP for thermal control. Important differences can be seen in the oxygen supply and associated structure of the CHXR unit. In the LOX system, the CHXR acts as a triple fluid heat exchanger. First, the liquid oxygen line “sees” the water loop, allowing the LOX to warm up in preparation for vaporization. In turn, the water loop cools down, minimizing the power requirement for the downstream SWME. The cooled water stream also “sees” the ventilation line that is being returned to the helmet. This exchange is twofold: 1) it removes waste heat in the vent stream that was added by the fans, and 2) it condenses humidity in the vent loop and adds it into the PTCL, ensuring that the airflow into the helmet is cool and dry (within relative humidity limits). The freezing of water from the LOX heat exchange is a potential concern in this configuration, though there are smart design options that can prevent this from occurring [16]. In the GOX system,

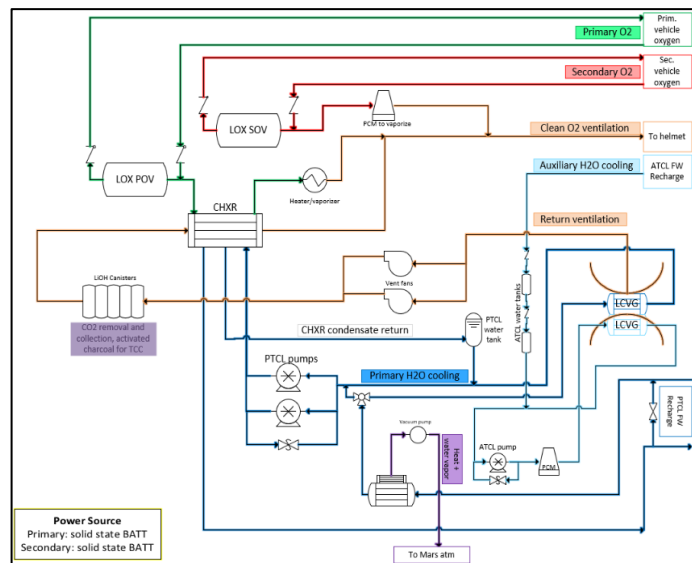
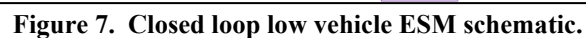
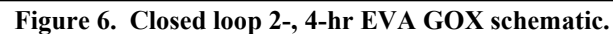


Figure 5. Closed loop 2-, 4-hr EVA LOX schematic.

Closed loop schematics for the 6- and 8-hour EVA durations are nearly the same as those for the 2- and 4-hour EVAs, with the only difference being the use of a Mars-sized SWME for primary thermal control rather than the SWME + VP. Considerations for the upsized SWME, SWME + VP, and sub-cooled PCM are the same as those listed for the open loop schematics.

PLSS architectures that optimize vehicle impacts were also identified for open, semi-open that they may yield a higher total PLSS mass re supporting such a suit is minimized. The schem all EVA times.

For the semi-open loop configuration, an RCA + boost compressor integrated with nanoporous silica is implemented for CO₂ removal, H₂O removal, and TCC, not unlike the GOX options recommended for the mass-optimized system. Alternatively, the closed loop architecture replaces LiOH canisters with the hollow fiber membrane (HFM) technology for CO₂ and humidity removal and a separate activated charcoal unit for TCC. Though it is a low TRL technology compared to other recommendations like LiOH or the RCA, the HFM shows a lot of promise for MxPLSS application due to its low mass, its regenerability, and its non-venting operation. F



option for CO₂ removal behind LiOH in the closed loop GOX and LOX PLSS architectures. An illustration of the closed loop HFM schematic is provided in Figure 7.

E. Summary of Schematic Recommendations

The following tables outline the mass, volume, power, and vehicle ESM requirements for the schematics presented above. Schematics are sorted by EVA time and are ordered from lowest to highest mass (including packaging). At shorter EVA times (2 and 4 hours), the lowest mass schematic option is the semi-open loop LOX architecture, which is paired with a cryogenic scrubber for combined CO₂ and humidity removal, and either a SWME + VP or VE EC radiator/SWME attachment for primary thermal control. At longer EVA times (6 and 8 hours), the lowest mass architecture is closed loop LOX, paired with LiOH and a CHXR for CO₂ and H₂O removal and an upsized SWME for primary thermal control.

Table 3. 2-hr EVA, 0.5-hr emergency ranked schematic options.

Schematic		Primary Subsystems	Secondary Subsystems	Mass (kg)	Volume (m ³)	Power (W)	Vehicle ESM (kg)
1	Semi-Open	LOX, ejector + pump, dual cryogenic scrubber, SWME + VP, activated charcoal	LOX + PCM vaporizer, pump, sub-cooled PCM	47.9	0.035	84.8	1657
2	Open	LOX + vent HX + heater, pump, SWME + VP	LOX + PCM vaporizer, pump, sub-cooled PCM	50.1	0.039	143.8	1181
3	Closed	LOX + heater, fan + pump, LiOH, CHXR, SWME + VP	LOX + PCM vaporizer, pump, sub-cooled PCM	50.2	0.041	96.9	1067
4*	Open	LOX + vent HX + heater, pump, radiator + HP	LOX + PCM vaporizer, pump, sub-cooled PCM	62.9	0.035	143.9	723
5	Closed	GOX + regulator, fan + pump, LiOH, CHXR, SWME + VP	GOX + regulator, pump, sub-cooled PCM	65.7	0.065	96.9	1477
6	Open	GOX + regulator, pump, SWME + VP	GOX + regulator, pump, sub-cooled PCM	70.1	0.075	84.8	2103
7*	Semi-Open	LOX + heater, fan + vent HX + pump, RCA + BC, radiator + HP, nanoporous silica	LOX + PCM vaporizer, pump, sub-cooled PCM	71.0	0.040	220.0	323
8	Semi-Open	GOX + regulator, ejector + pump, RCA + BC, SWME + VP, nanoporous silica	GOX + regulator, pump, sub-cooled PCM	73.2	0.069	207.9	1505
9*	Closed	LOX + heater, fan + vent HX + pump, HFM, radiator + HP, activated charcoal	LOX + PCM vaporizer, pump, sub-cooled PCM	73.7	0.051	99.7	372

*Low vehicle ESM option

Table 4. 4-hr EVA, 1-hr emergency ranked schematic options.

Schematic		Primary Subsystems	Secondary Subsystems	Mass (kg)	Volume (m ³)	Power (W)	Vehicle ESM (kg)
1	Closed	LOX + heater, fan + pump, LiOH, CHXR, SWME + VP	LOX + PCM vaporizer, pump, sub-cooled PCM	62.9	0.053	96.9	1640

2	Semi-Open	LOX, ejector + pump, dual cryogenic scrubber, VE EC radiator, SWME topping unit, activated charcoal	LOX + PCM vaporizer, pump, VE EC radiator	64.6	0.049	10.4	2342
3	Open	LOX + vent HX + heater, pump, SWME + VP	LOX + PCM vaporizer, pump, sub-cooled PCM	69.0	0.056	143.8	2134
4*	Open	LOX + vent HX + heater, pump, radiator + HP	LOX + PCM vaporizer, pump, sub-cooled PCM	77.6	0.048	143.9	1219
5*	Semi-Open	LOX + heater, fan + vent HX + pump, RCA + BC, radiator + HP, nanoporous silica	LOX + PCM vaporizer, pump, sub-cooled PCM	79.9	0.048	220.0	367
6*	Closed	LOX + heater, fan + vent HX + pump, HFM, radiator + HP, activated charcoal	LOX + PCM vaporizer, pump, sub-cooled PCM	83.1	0.059	99.7	411
7	Closed	GOX + regulator, fan + pump, LiOH, CHXR, SWME + VP	GOX + regulator, pump, sub-cooled PCM	85.4	0.090	96.9	2374
8	Semi-Open	GOX + regulator, ejector + pump, RCA + SG, SWME + VP, nanoporous silica	GOX + regulator, pump, sub-cooled PCM	96.5	0.093	86.1	2240
9	Open	GOX + regulator, pump, SWME + VP	GOX + regulator, pump, sub-cooled PCM	104.7	0.120	84.8	3933

*Low vehicle ESM option

Table 5. 6-hr EVA, 1-hr emergency ranked schematic options.

Schematic		Primary Subsystems	Secondary Subsystems	Mass (kg)	Volume (m ³)	Power (W)	Vehicle ESM (kg)
1	Closed	LOX + heater, fan + pump, LiOH, CHXR, SWME, activated charcoal	LOX + PCM vaporizer, pump, sub-cooled PCM	69.0	0.062	21.9	1951
2	Semi-Open	LOX, ejector + pump, dual cryogenic scrubber, VE EC radiator, SWME topping unit, activated charcoal	LOX + PCM vaporizer, pump, VE EC radiator	76.0	0.060	10.4	3155
3	Open	LOX + vent HX + heater, pump, SWME + VP	LOX + PCM vaporizer, pump, sub-cooled PCM	81.2	0.069	68.8	2827
4*	Semi-Open	LOX + heater, fan + vent HX + pump, RCA + BC, radiator + HP, nanoporous silica	LOX + PCM vaporizer, pump, sub-cooled PCM	83.2	0.050	220.0	415
5*	Open	LOX + vent HX + heater, pump, radiator + HP	LOX + PCM vaporizer, pump, sub-cooled PCM	86.6	0.056	143.9	1720
6*	Closed	LOX + heater, fan + vent HX + pump, HFM, radiator + HP, activated charcoal	LOX + PCM vaporizer, pump, sub-cooled PCM	86.8	0.062	99.7	453

7	Closed	GOX + regulator, fan + pump, LiOH, CHXR, SWME, activated charcoal	GOX + regulator, pump, sub-cooled PCM	92.2	0.100	21.9	2781
8	Semi-Open	GOX + regulator, ejector + pump, RCA + SG, SWME, nanoporous silica	GOX + regulator, pump, sub-cooled PCM	103.9	0.103	11.1	2655
9	Open	GOX + regulator, pump, SWME + VP	GOX + regulator, pump, sub-cooled PCM	124.7	0.149	9.8	5313

*Low vehicle ESM option

Table 6. 8-hr EVA, 1-hr emergency ranked schematic options.

Schematic		Primary Subsystems	Secondary Subsystems	Mass (kg)	Volume (m ³)	Power (W)	Vehicle ESM (kg)
1	Closed	LOX + heater, fan + pump, LiOH, CHXR, SWME, activated charcoal	LOX + PCM vaporizer, pump, sub-cooled PCM	74.6	0.067	21.9	2441
2*	Semi-Open	LOX + heater, fan + vent HX + pump, RCA + BC, radiator + HP, nanoporous silica	LOX + PCM vaporizer, pump, sub-cooled PCM	86.4	0.052	220.0	466
3	Semi-Open	LOX, ejector + pump, dual cryogenic scrubber, VE EC radiator, SWME topping unit, activated charcoal	LOX + PCM vaporizer, pump, VE EC radiator	87.4	0.070	10.4	3970
4*	Closed	LOX + heater, fan + vent HX + pump, HFM, radiator + HP, activated charcoal	LOX + PCM vaporizer, pump, sub-cooled PCM	90.5	0.066	99.7	498
5	Open	LOX + vent HX + heater, pump, SWME	LOX + PCM vaporizer, pump, sub-cooled PCM	93.0	0.080	68.8	3698
6*	Open	LOX + vent HX + heater, pump, radiator + HP	LOX + PCM vaporizer, pump, sub-cooled PCM	95.6	0.064	143.9	2222
7	Closed	GOX + regulator, fan + pump, LiOH, CHXR, SWME, activated charcoal	GOX + regulator, pump, sub-cooled PCM	98.6	0.107	21.9	3374
8	Semi-Open	GOX + regulator, ejector + pump, RCA + SG, SWME, nanoporous silica	GOX + regulator, pump, sub-cooled PCM	110.8	0.112	11.1	3264
9	Open	GOX + regulator, pump, SWME + VP	GOX + regulator, pump, sub-cooled PCM	152.6	0.190	9.8	6931

*Low vehicle ESM option

Note that while this study compares the lowest mass options found for open versus semi-open versus closed loop PLSS configurations, there are schematics that are not the lowest mass option within their own configuration category that trade better than options that came out on top in the other categories. For instance, Table 6 shows that 8-hour EVA schematics optimized for vehicle ESM in the semi-open and closed loop configurations trade better than the option optimized for PLSS mass in the open loop configuration. Additional low mass options in each configuration category have been taken into consideration and are being investigated in forward work.

IV. Schematic Assessment and Considerations

Further analysis of the schematics listed in Section III reveal some important considerations and trade-offs. These involve power and mass considerations concerning the use of the solid-state battery, environmental considerations concerning the system cooling capabilities of the variable emissivity electrochromic radiator under different operating conditions, and consumables and safety considerations concerning the use of LOX for oxygen supply in the primary and secondary PLSS subsystems.

A. Power Considerations

While high power draw technologies like the vacuum pump and boost compressor showed up in the lowest mass options for several schematics at shorter EVA times, these technologies require heavy components that utilize a large amount of power and are not particularly efficient. Furthermore, their large power requirements could have a more significant influence on PLSS mass than has been predicted due to utilization of the solid-state battery.

Modeling of the solid-state battery in GUS is currently based on performance parameters adopted from an experimental study found in literature which reported an energy density of over 900 W-hr/L (~550 W-hr/kg) for a lithium metal battery with a silver-carbon composite anode [17]. In comparison, Li-ion liquid batteries like those used in the xPLSS have a specific energy estimated at around 100 W-hr/kg. The influence of PLSS power requirement on battery mass for a battery with such a high specific energy is very low, so technologies with a large power draw like the vacuum pump or boost compressor do not trade as poorly with the solid-state battery as might be expected with a different type of battery. Due to the low TRL of the solid-state battery, it is unlikely that the specific energy estimate currently used in GUS accurately reflects what could be achieved by such a battery operating in a PLSS.

Table 7 compares the mass of Schematic 2 from Table 4 when implementing a SWME versus a SWME + VP for thermal control and a solid-state versus a Li-ion battery for power supply (90% battery efficiency assumed for both). For the solid-state battery option, the 75 W increase in power requirement from the vacuum pump technology results in only 0.55 kg increase in battery mass. The SWME + VP is 0.82 kg lighter than the upsized SWME, so the SWME + VP comes out as the lowest mass option when comparing overall PLSS mass. Alternatively, when a Li-ion liquid battery is used, there exists a 2.94 kg increase in battery mass from the 75 W of power required by the vacuum pump. The decrease in mass from switching from the upsized SWME to the SWME + VP is no longer substantial enough to offset the added mass of the battery, and the upsized SWME now comes out ahead for lowest overall PLSS mass.

This comparison underlines the need to further investigate solid-state batteries for PLSS-specific application. It also brings into question whether technologies like the vacuum pump and boost compressor are really the best options to enhance the SWME and RCA for

Table 7. Primary subsystem PLSS mass comparison for low and high power draw schematics using solid-state versus Li-ion liquid batteries.

4 hr EVA, 1 hr Emergency	LOX + heater, LCVG, fan + pump, LiOH, CHXR			
	Solid-state battery		Li-ion liquid battery	
	SWME	SWME + VP	SWME	SWME + VP
SWME mass, kg	6.04	5.22	6.04	5.22
Battery mass, kg	0.71	1.26	3.84	6.78
Primary PLSS mass (no packaging), kg	19.8	19.5	22.9	25.1

short EVA durations. Note that mass and power estimates from the GUS tool for SWME and RCA technologies with add-ons (e.g. vacuum pump, sweep gas, boost compressor) are still developing, given that these technologies were not originally intended to operate on Mars. Test data with such add-ons under the conditions of interest to support the calculations are a work in progress. The results shown here suggest a strong possibility that technologies with a lower power draw may end up trading better in the PLSS overall, despite having slightly higher masses on their own.

B. Environmental Considerations

Several of the semi-open loop LOX schematic recommendations utilize a VE EC radiator for primary thermal control paired with a SWME attachment as a topping unit, which is intended for warmer environments where the radiator cannot meet system cooling requirements on its own. This option is promising in that it provides water savings when compared to the use of an independent upsized SWME. Nevertheless, concern about the feasibility of the VE EC radiator in warmer environments calls into question whether the use of an upsized SWME would trade better than the VE EC radiator/SWME pair. Table 8 shows a primary subsystem mass comparison of Schematic 1 from Table 4 using the VE EC radiator/SWME pair versus an upsized SWME in Mars cold, nominal, and hot environments.

Sizing calculations for the VE EC radiator/SWME topping unit were executed under the assumption that the maximum metabolic rate capacity was a consistent condition over the entire EVA duration, which is an overprediction of the performance that would realistically be required. The results in Table 8 show that despite this overestimate, there are negligible mass differences between the two schematics in Mars cold and nominal environments, and only a slight favorability towards the upsized SWME schematic of 1.2 kg under the Mars hot condition. Since the VE EC radiator/SWME pair consumes less water than the upsized SWME in cooler environments, this technology option does have the potential to trade better depending on environmental conditions and how much of the PLSS exterior can be occupied by radiator panels. The use of the primary VE EC radiator for secondary subsystem thermal control is subject to the same environmental constraints, and data from GUS indicates that it would not be feasible under Mars hot environmental conditions unless another topping unit were added to the secondary thermal loop.

Table 8. Primary subsystem PLSS mass comparison for schematics using an upsized SWME versus a VE EC radiator with a SWME topping unit in different Mars environments.

4 hr EVA, 1 hr Emergency	LOX, LCVG, ejector + pump, dual cryogenic scrubber, activated charcoal, solid-state battery					
	Mars Cold		Mars Nominal		Mars Hot	
	Upsized SWME	VE EC radiator + SWME	Upsized SWME	VE EC radiator + SWME	Upsized SWME	VE EC radiator + SWME
Primary PLSS Mass (no packaging), kg	20.0	20.1	20.8	21.3	23.7	24.9
H ₂ O consumption per EVA, kg	1.59	1.21	1.80	1.66	2.32	2.32

The amount of heat the VE EC radiator can reject is directly dependent on its heat transfer surface area. In the above analysis, the surface area used is 0.855 m² (approximately 75% of the xPLSS surface area). Further 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 9 shows heat rejection capabilities of the VE EC radiator calculated in GUS under Mars cold, nominal, and hot conditions for radiator surface areas ranging from 0.855 m² to 1.105 m² (75-100% of xPLSS surface area). To remain consistent, these results were recorded at an emissivity of 0.9; however, the emissivity of the VE EC radiator in the realistic application could be programmed to increase or decrease based on heat rejection needs.

Table 9. VE EC radiator heat rejection capabilities using different heat transfer surface areas in different Mars environments.

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	~400	~580	59	65	72	76
Mars Nominal	~315	~495	204	227	251	264
Mars Cold	~280	~460	244	271	300	315

Results from Table 9 reveal that regardless of radiator surface area, a SWME attachment is always necessary to reach maximum system cooling requirements; however, it is not always necessary to meet average system cooling requirements. In Mars cold and nominal environments, an increase in the heat transfer surface area of the radiator results in a notable increase in heat rejection capability, which would in turn decrease the necessary consumption of H₂O by the SWME. Under Mars hot conditions, the radiator is less efficient and would require most of the heat rejection to be handled by the SWME attachment, but this warmer condition is a very conservative case (i.e., location specific and rare). To get a better perspective on the performance of the VE EC radiator under more realistic EVA conditions, a transient analysis was performed. Figure 8 shows transient heat storage results calculated in GUS for the primary subsystem of Schematic 1 from Table 4, not including the SWME attachment. The analysis assumes consistent Mars nominal conditions, but varying metabolic rates based on a standard metabolic profile.

The far-right column in Figure 8 shows that under nominal conditions, the VE EC radiator can meet system cooling requirements and maintain acceptable human heat storage limits (within -1.8 and 2.0 BTU/hr) for a wide range of metabolic rates. The evaluation does reveal a failure of the technology following a spike in metabolic rates to above 2000 BTU/hr for an extended period at the end of the 4-hour EVA, indicating that a SWME topping unit would be necessary to prevent overheating of the astronaut in stretches of higher metabolic rates. Still, the overall heat storage output

Time Minutes	Transient Profiles									Human Heat Storage Btu/lb
	Tsky K	Tgnd K	Atm Pressure psia	Wind Speed m/s	Qs,inc W/m2	Qir,inc W/m2	VF to Ground -	VF to Sky -	Metabolic Rate Btu/hr	
0.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	1025	0.00
12.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	1025	0.00
24.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	1025	0.00
36.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	1332	0.15
48.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	1332	0.30
60.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	1332	0.46
72.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	1332	0.61
84.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	1332	0.76
96.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	273	0.00
108.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	273	-0.03
120.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	273	-0.05
132.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	273	-0.08
144.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	2493	0.00
156.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	1332	0.15
168.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	1332	0.30
180.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	1332	0.46
192.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	1332	0.61
204.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	1332	0.76
216.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	2049	1.78
228.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	2049	2.80
240.0	139.82	212.04	0.124	10.0584	110.411	0.000	0.5	0.5	1025	2.58

Figure 8. Transient heat balance evaluation for the primary subsystem of Schematic 1 in Table 4 (LOX/cryogenic scrubber/VE EC radiator), not including the SWME topping unit.

suggests that the use of the SWME could be limited to a very brief time interval. As a result, the steady-state prediction of mass for the SWME attachment accompanying the VE EC radiator in this specific case would be an overestimation, and this technology could be sized down even further. Transient analysis of this schematic including the SWME topping unit reveals that for the same input conditions, the SWME attachment can meet system cooling requirements when sized for as low as 30 W of heat rejection. This equates to a total SWME attachment mass of 1.54 kg, compared to the 4.61 kg that was calculated for this component under the steady state evaluation.

C. Consumables & Safety Considerations

While semi-open loop LOX options with the cryogenic scrubber have the lowest PLSS mass at shorter EVA durations, they consume the most O₂. The cryogenic scrubber has a significantly lower mass compared to technologies like the RCA and LiOH, but it requires a flow rate of ~2.4 lb O₂/hr from the LOX tank. This flow rate requirement is higher than the flow rate requirement for the helmet, resulting in O₂ lost to the environment. The impact of this is very large at a system level, given that the extra LOX required for the PLSS with a cryogenic scrubber must be stored or somehow generated on the vehicle. This is not to say that competing low PLSS mass schematics do not also have high vehicle penalties. For instance, the LiOH technology is non-regenerable and requires extra canisters to be stored on the vehicle for replacement in between EVAs, resulting in a relatively high vehicle ESM. Still, the significant oxygen requirement by the cryogenic scrubber nearly always results in the highest vehicle ESM compared to any other closed-loop or semi-open loop schematic recommended.

Another important consideration for all the schematics involving LOX, particularly in the secondary subsystem, is safety. For secondary subsystems, the goal is to make the schematic as simple as possible. These schematics assume that there is no pump driving the flow of liquid oxygen in the ventilation loop because implementing a pump in the ventilation loop would add unwanted complexity. Without a pump, an optimistic assumption is that gravity-driven flow could provide the flow in a Mars environment, where the LOX outlet is at the bottom of the tank and a valve opens to allow LOX to exit. One of the potential issues with this would be if a crew member was disabled in some position where the bottom of the tank was not where it should be, though there could be a design where multiple lines come out of the LOX tank in different positions to ensure flow in the desired direction. Whether this would realistically work is unclear, and the risk associated with a potential failure is extremely high, as it would cut off oxygen supply to the astronaut. The use of gaseous oxygen in the PLSS does not present the same risks; however, mass estimates for the recommended GOX schematics are much higher than those for LOX, and none of them fall within the 62 kg PLSS mass goal even at a 2-hour EVA duration. Future work will include more testing to further investigate the feasibility of LOX.

V. Conclusion

This work was conducted as a continuation of the FY24 Mars Schematic Study (ICES-2025-90) to provide further guidance on the most feasible Mars PLSS schematics to develop into a workable test stand. Conducted from April 2025 to September 2025, upgrades were made to the Guided Utility Sizer (GUS) tool to allow for more sophisticated insight into technology impacts at the PLSS- and vehicle-level. Using an improved down-selection process, thousands of technology combinations were evaluated and compared in the upgraded tool, and higher-quality schematic

recommendations were made for open loop, semi-open loop, and closed loop PLSS configurations at EVA durations of 2, 4, 6, and 8 hours. The insights provided in this paper will be used moving forward to inform technology development, testing, detailed sizing analysis, and feasibility studies for MxPLSS prototype design and fabrication.

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.

References

- [1] P. Bailey, "Constellation Space Suit Element Portable Life Support System (PLSS) Schematic Selection Study," NASA, 2007.
- [2] C. Chullen, S. Sipila, K. Wells and S. McFarland, "NASA Extravehicular Activity Technology Roadmaps for Exploration – 2025 Status," in *54th International Conference on Environmental Systems*, Prague, Czech Republic, ICES-2025-61.
- [3] "Exploration Systems Development Mission Directorate (ESDMD) Moon-to-Mars Architecture Definition Document," NASA, 2024.
- [4] D. Lobmeyer, M. Oliver, E. Goodman and O. Lawson, "Martian Exploration Portable Life Support System Schematic Study," in *54th International Conference on Environmental Systems*, Prague, Czech Republic, ICES-2025-90.
- [5] M. Oliver, D. Lobmeyer, E. Goodman and O. Lawson, "Guided Utility Sizer," Version 1.0, Revision C, NASA, 2025.
- [6] M. Oliver, E. Quick, O. Lawson and I. LeJeune-Bolivar, "Down Selection of Architectures for the Martian Exploration Portable Life Support System (mxPLSS) – Final Report," CTSD-ADV-2343, NASA, 2025.
- [7] M. Oliver, D. Lobmeyer, E. Goodman and O. Lawson, "Guided Utility Sizer (GUS) Version 1.0 User's Guide, Revision A," CTSD-ADV-2197, NASA, 2024.
- [8] A. Carlson, N. Andersen and J. Collins, "In-Situ Resource Utilization Modeling of a Lunar Water Processing System," in *53rd International Conference on Environmental Systems*, Louisville, Kentucky, ICES-2024-53.
- [9] R. Mahon, M. Embrey, W. Bland, A. Pierson, M. Frenia and e. al., "Optimizing Portable Life Support System Sizing Given Crew Capabilities and In-Situ Recharging," in *54th International Conference on Environmental Systems*, Prague, Czech Republic, ICES-2025-539.
- [10] C. Campbell, "Subsystem Specification for the Exploration EMU (XEMU) Portable Life Support System (PLSS) Revision B," CTSD-ADV-780, NASA, 2020.
- [11] C. Brown and B. Miranda, "Extravehicular Activity System Sizing Analysis Tool (EVAS_SAT) Version 5.0 User's Guide," Jacobs JETS, 2008.
- [12] M. K. Ewert, T. T. Chen and C. D. Powell, "Life Support Baseline Values and Assumptions Document," NASA/TP-2015–218570/REV2, 2022.
- [13] C. Campbell, "PLSS MEL-PEL Tables Revision B," NASA.
- [14] G. Thomas, "Packaging Factors for Portable Life Support Subsystems Based on Apollo and Shuttle Systems," SAE Paper No. 932182, 1993, doi: 10.4271/932182.
- [15] N. Materer, E. Kadossov, A. Apblett, S. Shaikh, M. Komarneni and e. al., "Nanoporous Silica as a Regenerable Sorbent for Potential Integration into NASA's Trace Contamination Control System," in *52nd International Conference on Environmental Systems*, Calgary, Canada, ICES-2023-320.
- [16] B. S. Conger and G. C. Bue, "A Transient Thermal Model of a Neutral Buoyancy Cryogenic Fluid Delivery System," in *International Conference On Environmental Systems*, San Francisco, California, 1991.
- [17] Y.-G. Lee, S. Fujiki, C. Jung, N. Suzuki, N. Yashiro and e. al., "High-energy long-cycling all-solid-state lithium metal batteries enabled by silver–carbon composite anodes," *Nature Energy*, vol. 5, pp. 299-308, 2020, doi: 10.1038/s41560-020-0575-z.