Mars Portable Life Support System Status and Plan

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To get from Moon to Mars, development of a Mars-centered spacesuit to support extravehicular activity (EVA) must begin now. In an effort toward this goal, setup of a Mars Portable Life Support System (PLSS) team to evaluate schematics for a Mars Extravehicular Exploration Mobility Unit (MxEMU) is underway. As part of a previous study, a wide range of potential architectures were evaluated and compared to determine leading options for a Martian PLSS. Going forward, these schematics will inform technology development, testing, detailed sizing analysis, and feasibility studies. A Mars PLSS Test Bed will be developed and used to assess the schematics on a breadboard style configuration of components. Following results of the test bed, a packaged Design Verification and Testing (DVT) unit will be designed to fully test the Mars PLSS with a Pressure Garment System (PGS), forming a prototype MxEMU. This paper will discuss the roadmap to Mars PLSS maturation and its integration into a prototype DVT unit. Technical considerations for Mars and high-level requirements will be compared to the Lunar exploration EMU (xEMU), and forward work to answer technology and knowledge gaps will be addressed.

Nomenclature

BSLSS = Buddy Secondary Life Support System
CDRILS-M = Carbon Dioxide Removal by Ionic Liquid Sorbent for Mobility
CHX = Condensing Heat Exchanger
CO_2 = Carbon Dioxide
CWS = Caution and Warning System
DCM = Display and Control Module
DVT = Design Verification Testing
EMU = Extravehicular Mobility Unit
EVA = Extra-Vehicular Activity
GCM = Global Climate Model
GOX = Gaseous Oxygen
HFM = Hollow Fiber Membrane
HUT = Hard Upper Torso
ISS = International Space Station
IVA = Intravehicular Activity
JSC = Johnson Space Center
JPL = Jet Propulsion Laboratory
LCVG = Liquid Cooling and Ventilation Garment
LEO = Low Earth Orbit
LiOH = Lithium Hydroxide
MLI = Multi-Layer Insulation
MetOx = Metal Oxide
MxEMU = Mars Exploration Extravehicular Mobility Unit
OPS = Oxygen Purge System
ORU = Orbital Replacement Units
PCM = Phase Change Material
PLSS = Portable Life Support System
PGS = Pressure Garment System
RCA = Rapid Cycle Amine
SPE = Solar Proton Events
SWME = Spacesuit Water Membrane Evaporator
TCC = Trace Contaminant Control
TRL = Technology Readiness Level
WCH = Worst Case Hot
WCC = Worst Case Cold
xEMU = Exploration Extravehicular Mobility Unit

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I. Introduction

This paper introduces a new development effort towards the design and building of a Mars Exploration Extravehicular Mobility Unit (MxEMU). The Mars Portable Life Support System (PLSS) is being studied as part of an overall Mars spacesuit portfolio which includes Pressure Garment System (PGS) elements and human physiology testing. The Mars PLSS effort has undergone an initial schematic study [1] and is entering into performance studies and component development in preparation for the assembly of an integrated testbed. The unique environment on Mars poses new challenges for suit design, most notably the low atmospheric temperatures and large temperature fluctuations, the 3/8th gravity field, and the 95% carbon dioxide (CO_2) atmosphere at ~ 0.15 psia. As there have only been a handful of spacesuit development projects, this paper gives a review of historical EMU architectures to demonstrate design evolution and call attention to legacy elements that may or may not be applicable on Mars. Schematic recommendations from the initial study are provided, with a list of upcoming hardware development plans concerning the components considered most feasible for the Mars PLSS. The Mars mission architecture and PLSS design plan has been provided to highlight driving factors in planning and fabrication.

II. Historical Suit Development

Prior to delving into the Mars development effort, it is important to understand previous suit designs. A Mars suit will lean on designs and lessons learned from all suit development projects.

A. Apollo

The Apollo Extravehicular Mobility Unit (EMU) enabled astronauts to survive and work in the vacuum of space and on the Lunar surface. It consisted of three major subsystems: the Pressure Garment Assembly (PGA), the Portable Life Support System (PLSS), and the Oxygen Purge System (OPS).

The PGA was an anthropomorphic suit designed to maintain a pressurized environment while allowing mobility for mission tasks. It featured a neoprene-coated nylon bladder for pressure retention, a nylon restraint layer for structural integrity, and convoluted joints for flexibility. An integrated thermal micrometeoroid garment (ITMG) provided protection against extreme temperatures and micrometeoroid impacts. The ITMG included multi-layer insulation (MLI) which offers significant insulation in a vacuum environment; however, this type of insulation would not work well in the pressures experienced on the Mars surface. The suit included a polycarbonate bubble helmet with a Lunar Extravehicular Visor Assembly (LEVA) for glare and thermal protection, and gloves with Chromel-R metal fabric for abrasion resistance. For Apollo 15–17 missions, the A7LB suit introduced waist and neck mobility improvements and a diagonal entry closure to accommodate rover operations [27].

The Apollo PLSS was a backpack unit that supplies oxygen, removes carbon dioxide, controls humidity, and regulates temperature for crew members during extravehicular activity (EVA). The Apollo PLSS incorporated a passive porous plate sublimator for heat rejection, a liquid cooling garment (LCG) worn under the suit to transfer metabolic heat, and a lithium hydroxide (LiOH) bed for CO_2 removal. Early PLSS designs relied on gas cooling, but rising metabolic loads led to adoption of the LCG. The sublimator was another technology in the Apollo EMU that depends on the vacuum of space and would therefore be infeasible on the Mars surface. In addition to life support components, the PLSS houses a communications system and telemetry sensors. It has evolved through multiple configurations, culminating in the Apollo 15–17 version capable of supporting EVAs up to 7 hours, with an auxiliary water tank and improved oxygen capacity [27].

Mounted atop the PLSS, the OPS served as an emergency backup system, providing 30 minutes of oxygen flow at 3.63 kg/hr in case of PLSS failure. It could operate independently in contingency scenarios and was simplified to operate without heaters following thermal stability tests. For secondary cooling, a Buddy Secondary Life Support System (BSLSS) was included so a crewmember with a failed system could connect to an operable system on their "buddy" for emergency cooling needs while returning to the airlock [27].

Apollo suit development began in the early 1960s, incorporating lessons from Mercury and Gemini programs. The Apollo suits underwent extensive redesign after the Apollo I fire to meet stringent flammability standards, replacing many materials with nonflammable alternatives. Over the duration of the program, suits evolved from A5L prototypes to A7L and A7LB flight models, improving mobility, durability, and thermal protection. The EMU supported over 160 man-hours of Lunar EVAs across Apollo missions without major failures, enabling historic achievements such as the first Moon landing and extended exploration with the Lunar Rover [27].

B. Shuttle & ISS EMU

The Shuttle & International Space Station (ISS) EMU has similarities to the Apollo EMU but was conceived as a reusable EVA system—merging life support and suit hardware into a single, modular architecture. The Apollo EMU was a custom-fitted suit with a PLSS attached post-donning and connected by multiple exposed hoses, straps, and electrical lines. The integration approach used for the Shuttle and ISS EMU fundamentally shaped design choices, operations, and maintainability.

Whereas the Apollo EMU included intravehicular activity (IVA) suit capabilities with the PLSS detached, the Shuttle EMU design eliminated the need to protect crew under cabin depress using vehicle systems. A Hard Upper Torso (HUT) was added to the EMU that structurally mounted the PLSS and a Displays and Control Module (DCM). The DCM consolidated oxygen, water, power, communications, and status into a single front interface, and a single service and cooling umbilical (SCU) was used to simplify in flight recharge of oxygen, water, and battery power. Dense modular packaging raised PLSS packing density to ~80% (vs. ~40% for Apollo) and met a strict 18 ¾ inch front to back envelope for Orbiter hatch transfer [28].

To optimize zero gravity work, the Shuttle HUT introduced gimbaled shoulder bearings, wrist gimbals, and a waist bearing, substantially expanding upper body ranges (e.g., shoulder lateral–medial 205° vs. Apollo 135°; waist rotation 212° vs. 49°). Lower body mobility was deemphasized (no lunar walking), trading complexity for reliability and reduced mass. Fabric joints shifted from Apollo's dipped rubber convolutes to sewn flat pattern joints to increase flex cycle life and lower manufacturing cost [28].

The Apollo and Shuttle/ISS EMU systems both used closed loop ventilation with a sublimator and CO_2 scrubbing, but Shuttle integrated a motor driven fan/pump/water separator "triad" and a slurper/gas trap architecture that continuously removed humidity and recaptured condensate for reuse, reducing stored water needs compared to discarding to vacuum. A microprocessor driven Caution and Warning System (CWS) on the DCM added real time status, fault guidance, consumables tracking, and automated leak checks—features absent in Apollo's flag style warnings. Shuttle's Secondary Oxygen Pack (SOP) automatically flowed if suit pressure dropped, supporting open loop purges via helmet or DCM valves, while Apollo relied on manual activation [28].

A central Shuttle EMU requirement was multi-mission reuse across a broad range of astronaut sizes, achieved with flange mounted, interchangeable components (arms, legs, gloves, boots), adjustable cams and rings, and redundant axial restraints throughout the pressure garment. The flange mounted interfaces eliminated the need for vulnerable hoses and improved serviceability compared to Apollo, where external ventilation hoses and distributed controls increased risk and crew workload. Materials shifted to polyurethane coated nylon bladders (replacing Apollo's neoprene coated nylon) and heat-sealed seams to reduce leakage and extend life; soft goods targeted a six-year life and 462 pressurized hours, versus Apollo's single mission, male only custom suits with limited-life and slide fastener entries [28].

Subsequent Shuttle/ISS EMU development included planar fiberglass HUTs with serviceable ducts, on Orbit Replaceable Units (ORUs), refined Liquid Cooling and Ventilation Garment (LCVG) water/vent networks, Space-to-Space Extravehicular Mobility Radio (SSER) Ultra High Frequency (UHF) radios, and DCM controls for fans, water, and communications. Two CO_2 canisters have been used with Shuttle/ISS EMUs: LiOH (Shuttle) and regenerable MetOx (ISS). Glove evolution from 4000 series to Phase VI included adding a true thumb joint, soft wrist, heater circuits, and improved palm restraint for better dexterity. Power upgrades introduced an Increased Capacity Battery for longer wet life on ISS. These updates preserved Shuttle's integrated design philosophy while supporting station logistics [29].

Relative to Apollo, the Shuttle/ISS EMU embodies a transition from tailored, lunar mobility suits to modular, reusable, zero gravity work systems including tightly packaged life support, safer serviceability, improved caution and warning, less complex emergency oxygen operations, and sizing capabilities for a wide range of astronauts—all refined further for ISS operations.

C. xEMU

The Exploration Extravehicular Mobility Unit (xEMU), while not flown, represents a significant evolution from the Apollo and Shuttle/ISS EMUs, driven by the need for adaptability across diverse mission architectures including varied airlock interfaces and environments ranging from low Earth orbit (LEO) to lunar and Martian surfaces. Unlike previous designs tailored for specific missions, the xEMU employs a capability-based approach, enabling modular configurations for varied suit architectures and operational conditions. The xEMU is EVA-specific and is designed for 8-hour autonomous performance, exceeding Apollo's original 5–6 hour and Shuttle's 7-hour baseline. It targets up to 100 EVAs per mission and incorporates a two-fault tolerant system. Unlike Apollo's reliance on gravity-driven fluid separation, xEMU accommodates microgravity and variable gravity fields, eliminating vent/drain ports. Major innovations include:

- Variable Pressure Regulators: Allow suit pressures from 4.1–8.4 psid, enabling zero pre-breathe protocols and decompression sickness mitigation
- Rapid Cycle Amine (RCA) Swing-Bed System: Replaces consumable CO_2 scrubbers (LiOH and MetOx) and the condensing heat exchanger with a regenerable technology for continuous CO_2 and H_2O removal, reducing

maintenance requirements and microbial contamination risks associated with reuse of condensate from the Shuttle/ISS EMU condensing heat exchanger

- Suit Water Membrane Evaporator (SWME): Supplants sublimators, offering variable heat rejection and integrated gas removal that improves reliability and contamination tolerance, and is operational at pressures higher than those required for the sublimator [30]

The xEMU PLSS comprises primary and secondary oxygen loops, ventilation, thermal control, auxiliary thermal control, and vacuum manifolds. Both oxygen loops store oxygen at 3000 psia (compared to Apollo/Shuttle's 6000 psia Oxygen Purge System (OPS)/Secondary Oxygen Pack (SOP)), simplifying recharge and reducing ignition hazards. The ventilation system employs a Brushless DC motor powered fan, while thermal management uses a gear pump and SWME for efficient heat rejection. Auxiliary systems provide abort capability without requiring a "buddy" system like Apollo's BSLSS [30].

While the xEMU retains core functions from previous suits - oxygen supply and thermal loops - it introduces advanced controls, Micro-Electro-Mechanical Systems (MEMS)-based sensors, and stepper-actuated components for autonomous control. These changes reflect lessons learned, new technologies, and evolving mission requirements, positioning the xEMU as a versatile platform for future exploration. Note that the RCA and SWME technologies are designed for vacuum operations and will require modifications to be able to function on Mars [30].

D. Umbilical Suit EVA

Umbilical spacesuits represent an early and evolving approach to EVA, where astronauts rely on a tethered life-support system rather than a self-contained backpack. This design simplifies hardware but limits mobility and operational range.

NASA's Gemini program (1965–1966) introduced the first American spacewalks, using the G4C suit developed by the David Clark Company. These suits were connected to the spacecraft via an umbilical that provided oxygen and cooling, while exhaled gases were vented into space. The G4C featured multiple layers for thermal protection, a pressure bladder, and a restraint layer for structural integrity. Additional Chromel-R fabric was added for abrasion resistance during EVA. The umbilical system reduced complexity compared to later portable life support systems but imposes constraints on length away from the support craft. Gemini EVAs highlighted challenges such as suit stiffness and astronaut fatigue, influencing future designs [31].

During Skylab (1973–1974), NASA adapted Apollo's A7LB suit for orbital EVAs but replaced the PLSS with the Astronaut Life Support Assembly (ALSA) tethered umbilical system. The ALSA provided oxygen, cooling water, communications, and biomedical monitoring through a 20-foot hose. Skylab suits featured reduced thermal layers and simplified visor assemblies compared to Lunar suits, as orbital conditions were less demanding; however, entry zippers repositioned for easier donning in zero gravity sacrificed waist mobility. The tethered system allowed extended EVAs without the weight and complexity of a PLSS, though astronauts remained confined to the vicinity of the airlock [32].

SpaceX's modern EVA suits, first tested during the Polaris Dawn mission, are intended for short-duration EVAs. These suits maintain a sleek, lightweight profile and incorporate advanced features such as rotating joints for mobility, thermal management textiles, and a helmet with a heads-up display. Although SpaceX aims for scalable, mass-producible suits, early versions still rely on tethered connections for safety during private spacewalks. As with other recent spacesuit development efforts, SpaceX suits integrate modern materials and electronics and signal a shift toward commercial EVA operations [33].

As a novel concept for Mars, the University of Maryland is exploring a "BioBot" autonomous rover that could follow crew members on planetary surfaces, providing consumables via an umbilical [4]. This may be utilized if there are concerns with meeting mission and physiological requirements for a human on Mars using a PLSS alone.

III. Mars Mission Architecture

A. Mission Architecture

To understand EVA requirements, it is important to understand the mission profile to plan for when EVA's may be required and how many are needed. The Moon to Mars Architecture document, ESDMD-001, outlines the general plan for traveling to Mars [15]. A large driver for Mars suit design is the use of a conjunction or opposition trajectory. Conjunction requires a longer mission duration but uses less fuel and energy and allows for more time in Mars orbit (300-500 days). Opposition requires a shorter overall mission duration but expends more energy to get to Mars and only allows orbiting around Mars for a short time (10-50 days). Both trajectories have a travel time of 180-300 days one-way [15].

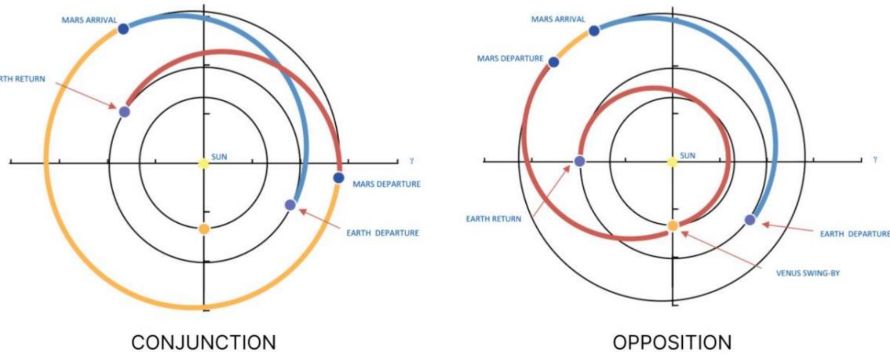

Figure 1. Mars trajectories [15].

Based on a decision memo from the Human Exploration and Operations (HEO), HEO-DM-1002, a couple reference missions are considered that help define the number of EVAs to be conducted on Mars [24]. The time frames in Table 1 all assume a 2039 departure that could vary by year, though the expected number of EVAs depends on the specific reference mission. More EVAs will drive up consumables requirements and may necessitate a different approach for suit sizing (with a focus on regenerability). The opposition mission #1 reference should be used for near-term analysis, research, and technology development, while the conjunction mission #3 reference should be considered for long-term stays on subsequent missions [24]. Assuming the first mission is the opposition mission #1 (per HEO-DM-1002), early, first generation Mars suits should be sized and designed for 20 EVAs total with margin. Later Mars suits for conjunction mission #3 will likely require new, renewable technology options that reduce the consumables mass for 125 EVAs and should be considered as a secondary factor. Margin for suit design should be considered for contingency, change in mission profiles, and flexibility in the future. The suit going to Mars would thus be designed for either 25 EVAs for a first-time mission and short stays, or 150+ EVAs for a long stay.

Table 1. Mars Reference Missions

	Transit "To, From" (days)	Orbit (days)	Surface (days)	Total (days)	Mission EVAs (#)	EVAs Design reqt.
Opposition mission #1	305, 375	50	30	730	20	25
Conjunction mission #2 (short stay)	200, 200	500	30	900	20	25
Conjunction mission #3 (long stay)	429, 429	365	300	1223	125	150+

The Moon to Mars Architecture document also tracks high level gaps for the mission to Mars architecture, including a section on EVA capability [15]. This gap emphasizes a few high-level development needs such as CO_2 removal, thermal control systems, dust mitigation, and maintenance/repair. Gravity, the atmosphere, mass reductions, and radiation are also noted as key items for consideration. The operation of a spacesuit in different environments is a very important factor. A journey to Mars consists of launching and landing from Earth, deep space transit, launching and landing from Mars, and a Mars surface stay. While not planned, a suit may be required for contingency in deep space. For Artemis and ISS, there have been both an EVA suit and an IVA suit for launching and landing. With zero atmosphere and similar thermal regimes to the Moon, a suit designed for the Lunar surface will likely operate the same in deep space; however, a suit designed for the atmosphere and thermal regime on Mars may not. Different suits may therefore be needed for IVA, launching and landing, EVA in deep space, and EVA on Mars. Further development may allow the EVA suit (in part or whole) to operate in both deep space and on Mars.

B. Mars PLSS Planning

The xEMU design effort, shown in Figure 2, due to funding levels and agency priorities, took ~15 years to evolve from its initial schematic study to an integrated Design Verification Testing (DVT) unit. It is expected the Mars PLSS design effort can lean on the lessons learned, team experience working on Artemis III, and available hardware to help complete breadboard and DVT unit development for Mars at a faster pace.

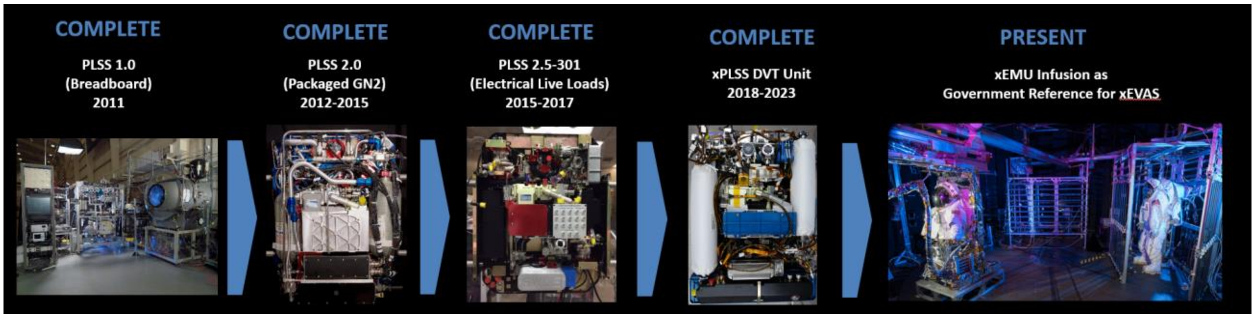

Figure 2. Evolution of xEMU.

The team is currently working toward development of a Mars PLSS testbed followed by a DVT unit. The anticipated development schedule from 2026 through 2031 is provided in Table 2. A schematic study was completed in 2025 that lead to the down-selection of several feasible Mars PLSS architectures, allowing for identification of key technologies to consider for further testing and verification in 2026 [1]. Technologies that showed promise will be developed into prototypes to prepare for testbed buildup in 2028, which will look like the "breadboard PLSS 1.0" testbed shown in Figure 2. Breadboard testing and DVT unit assembly will subsequently take place. Depending on the current state of hardware, the PLSS 2.0 and PLSS 2.5 DVT units (from Figure 2) may be combined to create a Mars DVT unit. It is expected that the Mars DVT unit would utilize only gaseous nitrogen, while future qualification units would be built with fidelity and safety protocols for running with oxygen. The shift between prototype component development and DVT development may continue for some hardware while the testbed is being constructed and tested, though it is expected that most prototypes will be ready for testbed integration by the end of 2027. A separate suit mass evaluation will be required to verify preliminary suit mass requirements [2].

Table 2. High Level Schedule for Development of a Mars PLSS

	2026	2027	2028	2029	2030	2031
System Performance Evaluation						
Mars Suit Mass Evaluation						
Prototype Component Dev.						
Mars PLSS Testbed Buildup						
Mars PLSS Testbed Testing						
DVT Component Dev.						
DVT Buildup						Future >

IV. Mars Suit Considerations

A. Environmental Considerations

Mars suit and PLSS design will be heavily influenced by environmental factors including the gravity field, atmosphere, temperature, radiation, and planetary dust. This section provides details of these environmental factors and operating conditions that may be encountered during EVA on Mars.

1. Gravity Field

Mars has a gravity field of 0.38 g, which is 2.3 times that of lunar gravity (0.17 g). Previous suit designs have not considered this increase in gravity, so a re-emphasis on mass will be necessary to develop the suit for Mars. While the most recent xEMU suit design weighs 391 lbs (177 kg), it is estimated that the Mars suit will not be able to exceed 229 lbs (104 kg, the mass required to accommodate the physiological limitations of a 5th percentile crewmember) [2].

2. Atmosphere

The atmosphere on Mars is composed of 95% carbon dioxide, with trace levels of gases including nitrogen, argon, oxygen, and carbon monoxide [3]. The atmosphere is much thinner than Earth's, with a maximum density around 20 g/m^3 and an average pressure of ~4.6 Torr. Atmospheric temperatures on Mars are also much colder than Earth's, averaging at -60°C. Wind speeds have been measured up to 50 m/sec (112 mph), but do not have the same impact as they would on Earth given the low atmospheric density [3]. Still, these high winds can lift significant amounts of dust, leading to dust storms that can cause strong diurnal radiative forcing of atmospheric temperature through enhanced heating and cooling [17].

Surface pressures on Mars can reach as low as 0.2 Torr or above 9 Torr, depending on location (elevation) and time of year. Elevations across the planet range from about -8 km to +21 km relative to the Mars datum. Aside from the Hellis Planitia impact basin (lowest location on Mars at 42.4°S 70.5°E), the Southern hemisphere is at a higher average elevation than the Northern hemisphere, resulting in lower pressures year-round. Large seasonal variations in pressure occur due to the condensation of carbon dioxide in the polar caps in the Winter and sublimation back to the gas phase in the Spring. Figure 3 illustrates pressure maps of Mars at times of the Martian year when the average global pressure is the lowest (typically during Northern Summer/Southern Winter) and highest (typically during Northern Autumn and Winter/Southern Spring and Summer) [18]. These maps were generated using data from the Jet Propulsion Laboratory (JPL) Mars Global Climate Model (GCM) with an assumed optical depth of 1.0 (moderately dusty atmosphere).

Locations where EVAs can take place on Mars may be limited by the atmospheric conditions that selected PLSS technologies can operate within. For instance, use of SWME technology for thermal control is contingent on low enough atmospheric pressure to allow water vapor venting to the surrounding environment. Accordingly, development of the first Mars suit will assume that landing sites for EVAs will be at locations where surface pressures do not exceed 7-8 Torr. In Figure 3, locations on Mars exceeding the 8 Torr pressure limit are colored red.

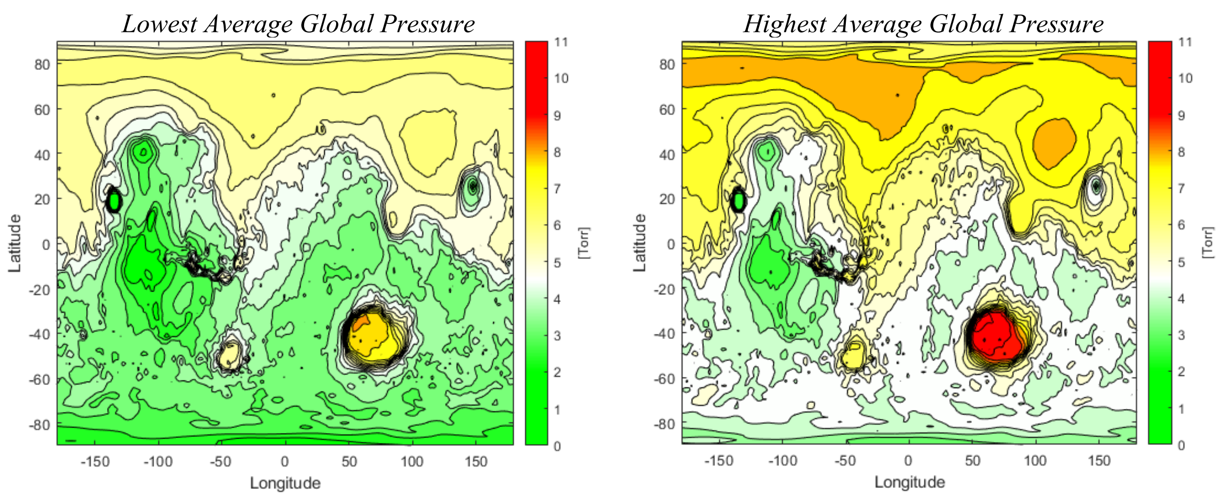

Figure 3. Pressure maps of Mars at times of year representing lowest and highest average global pressures.

3. Temperature

The Martian environment is characterized by low temperatures ranging from -143°C in polar regions during the winter to 20°C near the equator during daytime in the Summer. The coldest temperature is typically limited by the frost point of CO_2 [3]. Due to its thin atmosphere, surface temperatures on Mars can get much warmer than atmospheric temperatures, with estimated values from the Viking Orbiter Infrared Thermal Mapper of up to 27°C [19]. The maximum diurnal near-surface temperature on Mars can vary up to ~60°C, compared to only ~30°C on Earth. The seasonal averages of surface air temperatures can vary up to 90°C in Martian polar regions [20],[21]. Temperatures are influenced by the presence of suspended dust, which is most prevalent during the Northern winter/Southern summer [17]. Absorption of solar radiation by dust increases average daily temperatures and temperature ranges of the atmosphere, while decreasing average daily temperatures of the surface [20]. Regions of higher elevation on Mars are generally colder, with temperature decreasing by approximately 1.5°C per kilometer of altitude [22].

Using 3D data for one Martian year from the JPL Mars GCM, worst-case hot (WCH) and worst-case cold (WCC) surface locations were identified at latitudes of -50, -25, 0, +25, and +50 using an assumed optical depth of 1.0 (moderately dusty atmosphere). Figure 4 shows an elevation map of Mars with red and blue markers indicating locations with the hottest and coldest yearly surface temperatures, respectively. Minimum and maximum surface and atmospheric temperatures associated with each location are provided in Table 3. The GCM search was limited to locations that would be realistic for EVAs, with atmospheric pressures no greater than 7 Torr. As expected, the coldest locations correspond with the highest elevation regions, while the hottest locations tend to align with lower elevation regions where the denser atmosphere retains more heat.

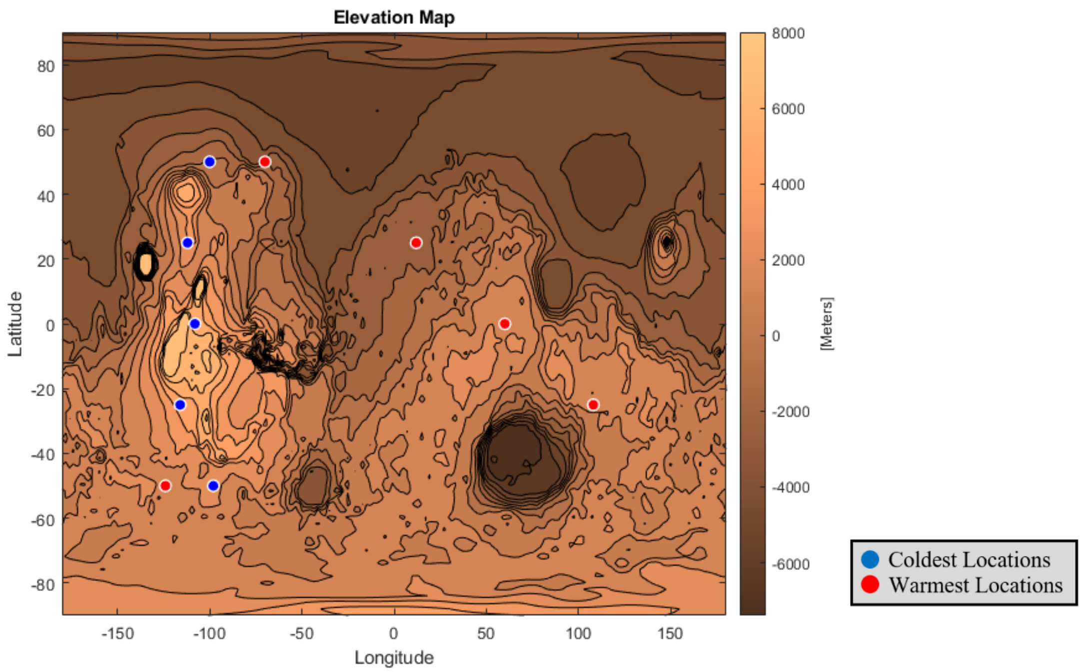

Figure 4. Elevation map of Mars with locations of hottest and coldest yearly surface temperatures at latitudes of -50, -25, 0, +25, and +50 and within a pressure maximum of 7 torr.

Table 3. Surface and atmospheric temperatures for worst-case hot (WCH) and worst-case cold (WCC) locations on Mars at latitudes of -50, -25, 0, +25, and +50 and within a pressure maximum of 7 torr.

Latitude	Condition	Longitude	Surface Temp, K		Atmospheric Temp, K	
			Minimum	Maximum	Minimum	Maximum
-50	WCH	-124	200	303	203	277
	WCC	-98	145	162	146	161
-25	WCH	+108	187	312	193	279
	WCC	-116	148	236	152	222
0	WCH	+60	178	303	183	271
	WCC	-108	144	265	146	237
+25	WCH	+12	148	288	153	260
	WCC	-112	146	265	154	248
+50	WCH	70	191	275	195	256
	WCC	-100	148	177	151	175

4. Radiation

While the CO_2 atmosphere on Mars offers roughly 27 g/cm^2 (16 lb/in^2) of protection from harmful radiation [3], radiation at the surface remains a major concern. Three primary radiation sources must be considered: continuous solar radiation, intermittent Solar Proton Events (SPEs), and persistent Galactic Cosmic Rays (GCRs).

Solar irradiance on Mars ranges from 493 W/m^2 at the lowest elevations to 717 W/m^2 at the highest elevations, with an average of about 589 W/m^2. For comparison, Earth receives an average of 1367 W/m^2. Ultraviolet exposure on Mars is significantly higher than on Earth; however, the CO_2 atmosphere absorbs nearly all wavelengths shorter than 2000 Å before they reach the surface [25].

Solar Proton Events—solar flares—are infrequent and typically last only a few days. Because EVAs are not expected to occur during these events, spacesuit designs generally do not account for SPE exposure. Galactic Cosmic Rays, on the other hand, can contribute to Single Event Effects (SEE) and Total Ionizing Dose (TID). Specific radiation levels that need to be accommodated in a Mars spacesuit will be determined in future assessments.

5. Dust and Soil

The composition of Martian soil is not fully characterized, but data from the Viking landers indicate a mix of fine-grained drift material, blocky fragments, and crusty or clod-like soil. This suggests that soil properties on Mars vary significantly depending on the landing site. Ground-level dust particles are generally expected to range from 100 to 1000 microns in diameter [3]. Unlike on the lunar surface, dust particles are expected to be suspended in the atmosphere. Airborne dust particles are anticipated to fall within the 0 to < 10 μm range, though minimum particle size and particle concentrations remain uncertain [25].

B. Shifts in Design Approach

1. *Suit Mass Prioritization*

To meet the mass requirements for operations on Mars, the suit's mass budget must be carefully prioritized throughout both the requirements development and the design process. Earlier EMU and xEMU systems were designed primarily for microgravity and lunar environments, where less gravity meant mass was a less critical constraint. For Mars, a shift toward a mass-centric design philosophy is essential to achieve a viable MxEMU configuration. Based on existing limited data, it is estimated a Mars suit can weigh no more than 229 lbs (104kg), 56% of the xEMU mass [2]. Several potential strategies for prioritizing and managing suit mass are outlined below.

The current xEMU has a two-fault tolerant requirement. Before the xEMU project, spacesuit architectures typically incorporated only single-fault tolerance. Returning to a one-fault-tolerant approach for Mars could significantly reduce mass by limiting the need for multiple redundant systems such as secondary pumps or fans or an auxiliary thermal loop. The Martian PLSS could return to using a BSLSS like Apollo. Similarly, xEMU introduced dual static seals in most locations for added redundancy, but reverting to single static seals would decrease component thickness and overall weight with minimal added risk. Because the suit undergoes extensive pressure testing at both the component and system levels—and because spare seals could be carried—this reduction in redundancy remains feasible. The current design also includes both a backplate for mounting components and a hatch on the HUT that interfaces with that backplate; combining these elements into a single structure would further reduce mass. Historically, the Apollo suits (weighing only 194 lbs (89 kg)) did not use backplate, relying instead on component structure to maintain suit integrity and reduce mass.

Increasing the volume of the suit may also enable more efficient design choices [5]. Additionally, component mass could be reduced by roughly 15% using advanced lightweight materials [6]. A life support architecture like Apollo's BSLSS could also be adopted, enabling longer walk-back capability and removing the need for a secondary cooling loop. Other options, though less desirable due to reduced regenerability or increased maintenance burden—could further reduce mass if required. Ultimately, a combination of these strategies will likely be required to achieve the Mars mass target.

If the above strategies do not reduce the suit mass enough to meet program requirements, EVA duration may need to be shortened to lower consumables mass and associated component mass. Secondary measures such as a consumables cache or umbilical systems with follower robots/rovers may alternatively be implemented to allow for re-charge during EVA. The distance of EVAs from the habitat may also be restricted to reduce the mass required for secondary/safety systems. Lastly, the crewmember selection criteria could become more selective to allow for operation of a heavier suit with more capability [2].

2. *Insulation*

Although not part of the PLSS itself, insulation strongly influences the amount of thermal cooling the system must provide. Historically, Multi-Layer Insulation (MLI) has been effective in hard-vacuum environments such as the Lunar surface and Low Earth Orbit (LEO). However, testing of several MLI samples across a range of pressures shows that at Mars atmospheric conditions—where pressures are consistently above 1 Torr—MLI performance is significantly degraded [7]. In hard vacuum (< 10^{-3} Torr), MLI can achieve heat fluxes below 1 W/m^2, but under Mars pressures the heat flux increases to more than 100 W/m^2. This roughly two-orders-of-magnitude increase indicates that traditional MLI will not provide adequate insulation on Mars.

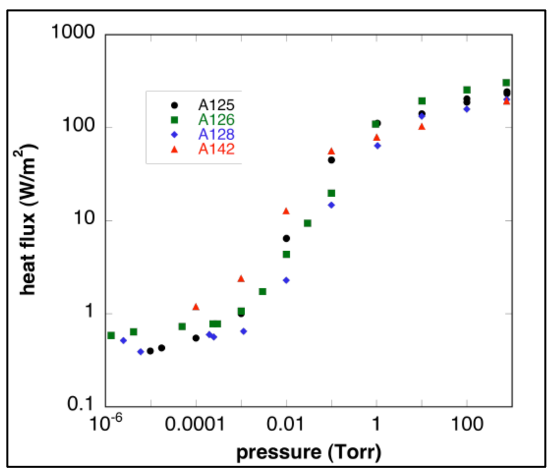

Figure 5. Heat flux versus interstitial gas pressure compared for four different MLI samples [7].

In lieu of MLI, alternative materials such as traditional synthetics or advanced aerogels (currently at low TRL) may be considered. Both materials are expected to be thicker and less effective than MLI in hard vacuum, but more feasible in the Mars atmosphere. Moreover, while Mars is very cold, it does not experience as extreme of temperature swings seen in deep space or on the Lunar surface, which may allow the overall system to operate with reduced insulation requirements. Layered or modular insulation concepts could also be employed, enabling the suit to adapt to different regions and times of day on Mars while minimizing cooling loads and material thickness during warmer conditions.

3. CO_2 Removal

All past CO_2 technologies including LiOH, MetOx, and RCA are being considered. RCA offers the advantage of regenerating during EVA without requiring removal and oven-regeneration like MetOx or disposal like single-use LiOH. However, RCA as is would not be recommended for an initial Mars mission due to Mar's high CO_2 concentration not allowing desorption. Several concepts for enabling RCA regeneration on Mars such as sweep gas systems, booster pumps, or thermal-swing approaches have been evaluated [8]. Booster pump and thermal-swing methods impose mass penalties too large to justify further consideration [8]. Sweep-gas would be sourced from the oxygen tanks and early concepts show highly variable performance in modeling. Initial estimates range from needing only a few pounds of sweep gas to requiring quantities comparable to the mass of the entire current PLSS and require physical testing to determine feasibility. The RCA at the base level also weighs 16lbs, which combined with vacuum access line mass and sweep gas mass may make it difficult to trade for overall mass on back for Mars. The sweep gas mass as a consumable may also trade closely to LiOH. MetOx remains an option, however, its weight is relatively heavy at approximately 32 lbs (15 kg) per canister which tends to push it out of the trade space. LiOH is the lightest option at 6.4 lbs (2.9 kg) per canister, but it is non-regenerable.

Several new technologies are currently being explored for CO_2 removal in the Mars PLSS including Carbon Dioxide Removal by Ionic Liquid Sorbent for Mobility (CDRILS-M) system [9], and Hollow Fiber Membranes (HFM) using liquid sorbents [10]. The liquid-sorbent approaches remain low-TRL but offer the potential for a regenerable CO_2 removal system suitable for Mars, provided their total system mass can be kept within the PLSS mass budget.

If the mass budget allows, a regenerable CO_2 removal system would be preferred; however, LiOH may be the most mass-efficient solution for meeting EVA duration and physiological requirements, particularly for short missions with a limited number of EVAs. For missions requiring many EVAs, the cumulative mass of LiOH canisters becomes a significant drawback.

4. Thermal Control

The Spacesuit Water Membrane Evaporator (SWME) used in the xEMU relies on the vacuum of space for operation. Although its performance may be reduced in a non-vacuum environment, testing indicates that the SWME could still function on Mars [12]. The system has been evaluated at pressures up to 10 Torr (1333 Pa), which is near the upper limit of expected Martian surface pressures; typical operating sites on Mars are likely to be at lower pressures. The SWME normally operates at 50°F (10°C), though slightly higher operating temperatures may be required based on saturation-pressure behavior, as shown in Figure 6. Sweep gas could be incorporated if needed, but it only provides meaningful benefits at the highest Martian pressures and lowest outlet temperatures.

It is important to note that the existing tests did not account for airflow within the suit's internal volume or for any filtration that may be required to prevent Martian dust from entering the SWME. Additional testing will therefore be necessary to validate performance under relevant Mars conditions. If thermal loads remain comparable to current requirements, the SWME may need to be scaled up or supplemented with sweep gas. On the other hand, alternative thermal control strategies or environmental factors on Mars may reduce the cooling demand placed on the SWME.

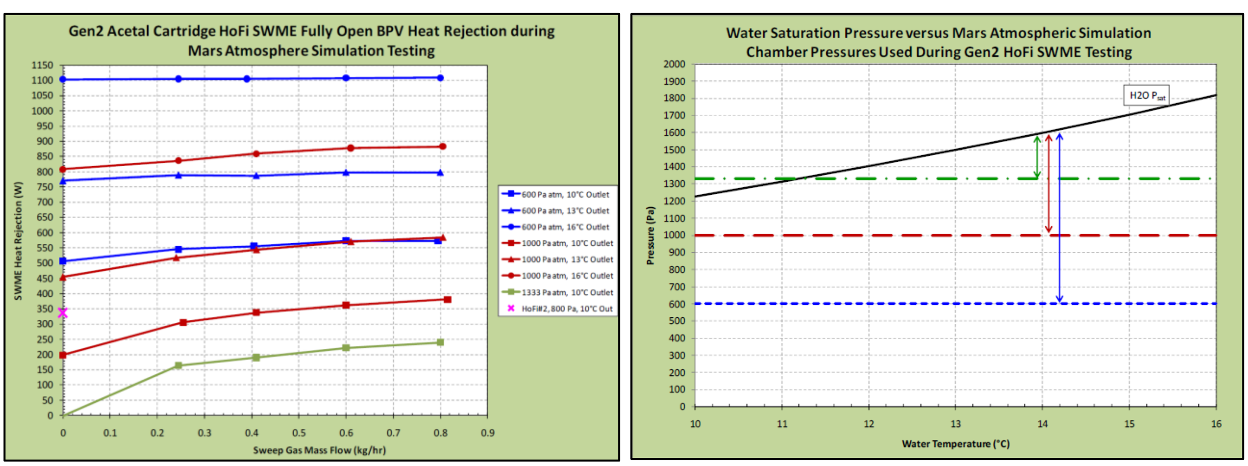

Figure 6. (a) Mars SWME testing with sweep gas (b) Mars SWME saturation pressure vs. temperature [12].

The thin atmosphere on Mars creates an opportunity to leverage convective cooling, something not possible in the hard vacuum of space. Prior Mars missions have already demonstrated successful helicopter flight, and associated testing has shown that fans can operate efficiently in the Martian environment [14]. For example, a small commercial fan that would normally draw 100 W on Earth required only 5 W in Mars conditions while still producing roughly the same volumetric flow rate (~5 m^3/min). Although this corresponds to a very high volumetric flow on Earth, the low atmospheric density on Mars reduces the mass flow rate to about 5 kg/hr. Such airflow could potentially serve as sweep gas to support SWME operation, though appropriate filtration would be necessary to mitigate dust.

The same fan technology could also enable a forced-convection heat exchanger. A theoretical analysis suggests that, on Mars, a 6.4 W fan with a 0.5 kg mass could dissipate approximately 1 kW of heat load [13]; however, this estimate assumes a relatively high working-fluid temperature of ~400 K, whereas the suit's cooling loop would operate closer to ~300 K. As a result, performance would depend strongly on ambient Mars temperatures, and additional cooling components might be required in warmer environments.

5. Dust Protection

Because Mars has an atmosphere containing suspended dust, it is likely that dust could infiltrate the PLSS through the vent paths intended for SWME exhaust. If this occurs, dust may accumulate on internal components or enter the SWME cavity, where evaporating water could mix with the dust and form a mud-like residue. To prevent this, filters will be required on the PLSS outer mold line to block dust intrusion, though back pressure from the filters may reduce the SWME's operational performance.

C. Mars Suit Deep Space Operation Contingency

As a contingency case for a deep space transit emergency EVA, the spacesuit for Mars may also need to be designed to operate in deep space and on Mars. To consider this, the requirements for each environment are considered and compared here. Furthermore, elements in part or whole with a lightweight suit for Mars may also be options to consider for other applications in LEO or lunar, so cross compatibility may be desirable. A comparison of high-level environmental factors is shown in Table 4.

The thermal and atmosphere on Mars provide significant challenges to implement, although there is opportunity for design with both environments in mind, though it could increase on back mass. The insulation on the PLSS may need to be swapped out for MLI based insulation when in deep space. Thermal control may be sized differently for the colder environment on Mars, so larger heat rejection systems may be required for hot cases in deep space that may not be required for Mars. If the Mars suit implements convective cooling, a different heat rejection system will be needed for deep space.

Mars Protection Garment System may not provide adequate protection against the extreme thermal conditions of deep space. Those environments may require a return to MLI, which is typically integrated into the garment design. As a result, separate configurations of the pressure garment system (PGS) would likely need to be developed for Mars versus Lunar or deep space use.

Table 4. Environmental Comparison Table

	Microgravity/LEO/Deep Space	Lunar	Mars
Gravity	~0	1/6 G	3/8 G
Temperature [34]	138 - 337K (sink temperature)	93 - 377K (sink temperature)	144 - 279K (atmosphere)
Pressure	~0	~0	0.2-9 torr
Dust	No	Yes	Yes - airborne

V. Mars PLSS Technology Development

A. Schematic Study

A Mars schematic study evaluated different PLSS configurations for Mars [1]. Each configuration was assessed for 2-, 4-, 6-, and 8-hour EVA durations. This process identified many key technologies to consider for further evaluation and development which are listed in the next section.

Across all cases, the lowest-mass GOX-based suit design used a LiOH canister as the primary CO_2 removal method, although this does not consider vehicle mass [1]. Regenerable, closed-loop CO_2 removal technologies are being explored to reduce overall vehicle mass and limit reliance on single-use LiOH cartridges, though these systems are expected to increase suit mass.

This schematic study also identified liquid oxygen (LOX) systems as the lowest-mass option across several configurations [1]. However, LOX remains a low-TRL technology for suit integration and presents multiple operational and safety challenges beyond simply storing a tank in the PLSS. Charging LOX inside the habitat would introduce cryogenic-handling hazards, increased fire risk from spills or venting, and potential explosion risks. LOX would also need to be supplied across multiple mission elements including the lander, habitat, consumables cache, and rover, adding logistical complexity. Operationally, LOX would require repeated charging and discharging for testing and checkout, as well as final pre-EVA connection and post-EVA disconnection, all of which would need to be performed with gloved hands. Given these concerns, the next most viable option is a system utilizing gaseous oxygen (GOX), which avoids many of the integration and safety risks associated with LOX.

B. Technology Development and Testing

Many existing technologies are being considered, though new and potentially extensive development efforts will be required for many as even if the technology is well understood. Designing and fitting any components in a new Mars PLSS will be a challenge. In the vent loop, GOX, LiOH, RCA, flowmeters, Condensing Heat Exchanger (CHX), check valves, and CO_2 monitoring technologies are being developed and considered. For the thermal loop, a new Mars SWME is being developed and considered. An auxiliary thermal loop is also being considered, using a BSLSS type system that can interface with a partner's thermal loop in the event of a primary loop failure. Lastly, new batteries, avionics, and filters to protect the internal PLSS volume, are also being developed.

Several lower-TRL alternatives are being explored for various pneumo-hydraulic subsystems. These include concepts such as convective radiators for thermal control, liquid-amine CO_2 removal systems (CDRILS-M or HFM), regenerable Trace Contaminant Control (TCC), and Phase Change Materials (PCM) for supplemental cooling.

A significant number of existing PLSS technologies are expected to carry forward to Mars with minimal modification. This includes components such as fans, pumps, gaseous oxygen regulators and tanks, the LCVG, pressure sensors, activated carbon for TCC, and the thermal control ball valve. While new vendors or design variations may be evaluated, there has been no substantial effort to alter the fundamental designs of these elements for either Mars or Lunar missions since development of the xEMU.

Multiple technology development paths are being explored both internally and with external vendors. Most early-stage (low TRL) technology development work is progressing through Small Business Innovation Research (SBIR) efforts. For more details, the technologies that are currently under active investigation or development include:

1. *Spacesuit Water Membrane Evaporator (SWME)*

A new SWME development effort is being started to explore alternative designs that improve performance and adapt the technology for Mars operations. This work includes evaluating different sizing approaches, determining whether sweep gas assistance is necessary under Martian pressures, and investigating new membrane materials and fiber architectures that may enhance efficiency and durability.

2. *Condensing Heat Exchanger (CHX)*

The current xEMU design relies mainly on the RCA for both CO_2 and humidity removal. Switching to LiOH or other CO_2 removal systems may eliminate the humidity removal capability, meaning Mars suits will need to reintroduce a condensing heat exchanger (CHX). Multiple CHX designs are currently under evaluation for the Mars PLSS. A CHX used for Mars may need to be fully gravity-independent so it can operate reliably in multiple orientations in the Martian environment, as well as zero-g if the PLSS for Mars is considered contingency for transit. The system must be capable of condensing and collecting water from the ventilation loop, with recovered water being stored or recaptured for use during the EVA.

3. *Lithium Hydroxide (LiOH)*

A Lithium hydroxide package design for Mars is being explored. LiOH was used for previous suits, although it has been many years since the last time one for a suit was built, so a new development effort is being started. LiOH is exploring both more traditional granule-based sorbents, or newer solid sheet blocks of LiOH. Trace TCC using activated carbon and filters may be integrated to provide one single integrated cartridge for easy removal/replacement between EVAs.

4. *Rapid Cycle Amine (RCA) Swing bed*

An RCA swing bed and associated amines have been in development with multiple vendors for lunar already. The RCA is being investigated for Mars implementation. A sweep gas approach is being tested to determine the requirements to infuse RCA on Mars. Pending the results of that test, the RCA will be traded against the other technologies in consideration for CO_2 removal on Mars.

5. Carbon Dioxide Removal by Ionic Liquid Sorbent for Mobility (CDRILS-M)

Honeywell is developing a CO_2 removal system that uses ionic liquid to trap carbon dioxide from the ventilation stream [9]. This system can also absorb H_2O, potentially eliminating the need for a CHX. The system can be regenerated in between EVAs by connecting the ionic liquid tank to a CO_2 stripper in the vehicle.

6. Hollow Fiber Modules (HFM)

Reactions Systems is developing a CO_2 removal system that uses a liquid amine sorbent to remove CO_2 from the ventilation loop [10]. This technology can also perform humidity removal, potentially eliminating the need for a CHX. Regeneration can take place via exposure to heat and vacuum during or after and EVA.

7. Phase Change Material (PCM)

Phase change materials such as super ice are being considered as a lightweight backup option for the auxiliary thermal control loop in the PLSS. PCMs do not trade well for thermal control over the course of a full EVA due to the large dependency of component mass on EVA time. They do, however, act as a strong option for short-duration emergency scenarios compared to options like a backup SWME or a BSLSS.

8. Batteries

Battery development for the Mars suit includes investigation of next-generation solid-state technologies, which offer promising performance and safety benefits but remain at low TRL. In parallel, the Mars architecture is shifting toward a monolithic battery design rather than the multiple discrete battery packs and rack structure used in the xEMU. Consolidating the battery into a single integrated unit reduces packaging mass and simplifies system integration, helping meet the stringent mass constraints of the Mars PLSS.

9. Avionics

New avionics will be required for the Mars PLSS, with an emphasis on lighter-weight, radiation-tolerant, and lower-power components. Since xEMU development began, newer chipsets have become available that could simplify the avionics architecture while reducing mass and power consumption. Efforts are also underway to evaluate lighter-weight avionics box designs to further reduce system mass. In addition, the Caution and Warning System (CWS) will need to account for isolated or limited mission control support, incorporating more autonomous decision-making processes due to the communication delay with Earth.

10. Forced Convection Heat Exchanger

Convective heat exchangers using the cold Mars atmosphere as one of the fluids are being evaluated as an alternative to the traditional SWME for removing metabolic heat [13], [16]. This approach remains relatively low TRL due to lack of testing at near vacuum pressures and is currently in the theoretical-analysis stage, though existing research indicates promising potential for Mars operations. A major advantage of a convective system is the significant reduction in water consumption, since it avoids the large volumes of water that the SWME exhausts into the Martian environment.

11. Filters

To be able to protect from the 0-10um size dust, high efficiency filters are being considered to protect the PLSS internal components while also allowing the SWME to exhaust through the PLSS internal volume.

12. Feedwater Supply Volume Sensing

A new development effort is underway to enable volume sensing for a flexible water bladder, applicable to both Lunar and Mars suits. Emerging technologies aim to provide continuous volume sensing throughout the entire EVA, offering more insight than legacy methods [23]. Previously, the EMU relied on a secondary bladder that would crack open once the primary bladder was depleted, using the resulting pressure change as a sensing mechanism. This approach has known reliability concerns and only provides an emergency-level warning, signaling that the crew member must return to the airlock before the secondary bladder is depleted.

13. CO_2 and Gas Sensing

Multiple vendors are developing lighter-weight approaches for CO_2 sensing as well as new sensor technologies capable of measuring oxygen concentration inside the suit. Historically, pre-breathe procedures have relied on extended purge durations to ensure the suit atmosphere approaches 100% oxygen, largely because reliable, compact O_2 sensors were not available. There has always been a desire to measure both O_2 and CO_2, but previous sensor technologies have been too heavy, bulky, or insufficiently stable for long-duration missions and the calibration requirements of deep space travel. Newer sensor concepts aim to overcome these limitations and provide continuous, high-fidelity atmospheric monitoring within the PLSS [26].

14. Advanced Trace Contaminant Control (TCC)

New regenerable TCC media are being developed that can be regenerated using the vacuum of space. Historically, activated carbon has been used in all suit designs, but it becomes expendable after a limited number of EVAs. A key advantage of regenerable TCC media is the potential to integrate it with RCA beds for simultaneous regeneration, though RCA itself is not a leading candidate for Mars. Advanced TCC media will be evaluated for Mars missions to reduce the quantity of expendable TCC required; however, traditional activated carbon may remain the preferred option for early missions where mass and system simplicity are prioritized.

15. Check Valve

Previous xEMU check valves have struggled to meet stringent back leakage limits and minimal pressure drop requirements. As a result, a new technology development effort has begun to investigate alternative check valve designs that can satisfy these performance needs while remaining lightweight enough for Mars PLSS integration.

16. Flowmeter

A new flowmeter capability is being planned to enable continuous measurement of suit ventilation loop flow rate. Previous EMU suits on the ISS relied only on a flow switch integrated with the check valve, which provided a simple on/off indication once flow exceeded a threshold and could not measure continuous flow parameters. Depending on the final CHX design, a single differential pressure sensor may be sufficient to provide a rough flow rate estimate that can still detect emerging flow-related failures. The overall schematic is still being evaluated to determine the most effective and lightweight approach for flow monitoring.

17. Lightweight Materials

A broad effort is underway to reduce mass across all PLSS components and structural elements. This includes conducting a market survey of advanced lightweight materials, performing environmental testing to validate their performance in extreme spaceflight conditions, and incorporating promising candidates into current hardware designs. Materials under consideration include machined PEEK and Ultem, as well as additively manufactured Windform (nylon + carbon fiber) [6].

VI. Conclusion

Designing a Mars PLSS requires accounting for the planet's unique environmental factors, including 3/8th gravity, wide thermal ranges, and a thin CO_2-dominated atmosphere. Building a Mars suit will also require a paradigm shift in which masses become a primary design driver, affecting both technological component selection and the materials used throughout the system. New CO_2 technologies, or legacy systems like LiOH, will need to be considered, as current CO_2 removal methods like the RCA do not perform well in the Martian atmosphere. The atmosphere also introduces thermal control challenges; traditional multilayer insulation (MLI) is ineffective on Mars, yet the presence of a gas environment opens the trade space for convective cooling approaches. Despite being very cold, temperature regimes on Mars are not as extreme as those in deep space and Lunar environments, providing some flexibility for thermal control and insulation design. For an initial Mars PLSS schematic, lightweight options will be essential. Liquid oxygen offers the lowest-mass architecture, but operational and safety constraints may ultimately require gaseous oxygen to be the basis of design. Many additional components and subsystems will need to be traded, developed, and tested as part of an early integrated testbed effort.

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