

NASA Extravehicular Activity Technology Roadmaps for Exploration – 2025 Status

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As the National Aeronautics and Space Administration (NASA) sets its goals toward Earth’s Moon and Mars, a spacesuit design tolerable of gravity, dust, and Mars’s atmosphere will be needed. NASA has used roadmaps as the means of documenting actionable plans for strategizing technology developments needed to meet NASA’s missions. In 2024, NASA created extravehicular activity (EVA) technology roadmaps for the Moon to Mars (M2M) strategy. These roadmaps visualize an actionable path to EVA capabilities needed for Mars exploration. Although technologies have been developed and matured over the decades to advance EVA systems, technology gaps remain. Over the last 15 years, major steps were taken to advance the technology with the Exploration Extravehicular Mobility Unit (xEMU) government reference design at the Johnson Space Center (JSC) in Houston, Texas. The xEMU builds on the lessons learned of the Apollo, Space Shuttle, and International Space Station (ISS) EMUs, evolving the technology to increase performance for extreme environments. To help create and sustain a presence on the Moon, NASA has procured EVA services from industry through the Exploration EVA Services (xEVAS) contract. NASA will now focus on sustained human lunar surface exploration and a mission to Mars. Therefore, the technology development and detailed design to enable the sustaining class lunar missions, as well as later missions to Mars, are still under NASA’s purview and responsibility. NASA’s leadership has set goals and objectives related to the Agency’s vision and a M2M strategy. This paper covers the maturation and development of the spacesuit technology and updates the EVA technology roadmap for the M2M Program in alignment with NASA’s vision.

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Nomenclature

ADD	=	Architecture Definition Document	<i>ml</i>	=	milliliter
AFR	=	Advanced Fuel Research	M2M	=	Moon to Mars
<i>BTU/hr</i>	=	British Thermal Unit per hour	NESC	=	NASA Engineering and Safety Center
CDRILS	=	CO ₂ Removal by Ionic Liquid System	NH ₃	=	ammonia
CO ₂	=	carbon dioxide	O ₂	=	oxygen
Comm	=	communications	PCI	=	Precision Combustion Inc
DC-DC	=	Direct Current	PGS	=	Pressure Garment System
DTO	=	Developmental Test Objective	Ph	=	Phase
ECLSS	=	Environmental Control and Life Support System	PLSS	=	Portable Life Support System
EHP	=	EVA and Human Surface Mobility Program	PR	=	pressurized rover
EIO	=	Earth Independent Operations	psia	=	pounds per square inch absolute
EMU	=	Extravehicular Mobility Unit	RCA	=	rapid cycle amine
EPG	=	environmental protection garment	SA9T	=	art sorbent
EVA	=	extravehicular activity	SBIR	=	Small Business Innovative Research
EVVA	=	Extra-Vehicular Visor Assembly	SCLT	=	Strategic Capabilities and Leadership Teams
FOM	=	figures of merit	SERFE	=	SWME Express Rack Flight Experiment
FY	=	Fiscal Year	STIP	=	Strategic Space Technology Investment Plan
<i>g</i>	=	Earth's gravity	STMD	=	Space Technology Mission Directorate
GFE	=	government-furnished equipment	STTR	=	Small Business Technology Transfer
GUS	=	Guided Utility Sizer	SWaP	=	Size, Weight, and Power
GW	=	Gateway	SWME	=	Suit Water Membrane Evaporator
HFM	=	hollow fiber membrane	TBC	=	to be considered
HITL	=	human-in-the-loop	TBD	=	to be determined
HLS	=	Human Landing System	TBS	=	to be stated
HUT	=	hard upper torso	TCC	=	trace contaminant control
ISS	=	International Space Station	TI&P	=	Technology Integration & Partnerships
IVA	=	intravehicular activity	TRL	=	Technology Readiness Level
JSC	=	Johnson Space Center	TVAC	=	Thermal Vacuum
<i>K</i>	=	kelvin	VI	=	six
KPP	=	key performance parameters	<i>W</i>	=	watt
<i>lbs</i>	=	pounds	w/o	=	without
LEO	=	Low Earth Orbit	xEMU	=	Exploration Extravehicular Mobility Unit
LTV	=	lunar terrain vehicle	xEVAS	=	Exploration Extravehicular Activity Services
MCO	=	Mars Campaign Office	xPGS	=	Exploration Pressure Garment System

I. Introduction

THE work outlined in this paper is the culmination of years of effort by two primary groups at National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC). The first group is the Space Suit and Crew Survival Systems Branch which resides organizationally within the Crew and Thermal Systems Division which is one of 7 divisions within the Engineering Directorate at JSC. The work from this group has cultivated advanced space suit prototypes for decades and is primarily responsible for the development, assembly, and testing of the Exploration Extravehicular Mobility Unit (xEMU) advanced space suit government reference design. The second group is the Technology Integration and Partnerships (TI&P) Office of the Extravehicular Activity and Human Surface Mobility Program (EHP). This group is responsible for collaborating with engineering organizations across NASA to maintain technology development roadmaps to drive sustaining lunar and Mars exploration development.

The purpose of this paper is: (1) to share the progress that NASA has made toward advanced space suit hardware capable of supporting lunar explorations of the near future, including the current context of Extravehicular Activity (EVA) development for upcoming Artemis missions, and (2) to disseminate the technology development roadmaps that NASA views as the critical capabilities and enabling technologies that are required to provide EVA capability for future sustaining-class Artemis missions (Artemis V+) as well as human exploration of Mars.

This paper covers the maturation and development of the spacesuit technology and updates the EVA technology roadmap for the M2M Program.¹ The EVA roadmap visualizes an actionable plan to realize EVA capabilities needed for Mars exploration. It is in alignment with both NASA's Exploration Architecture² and Civil Space Shortfalls³ that identify a technology required to meet future mission needs. Roadmaps facilitate discussion, decision making, and planning for programs and development projects; they are not expected to accurately depict the details and statuses of the projects and tasks appearing within the plans.

II. Historical Strategy

EVA spacesuit development, since the first spacewalk in 1965, has captured system changes needed to accomplish the mission, adapt to the destination environment, improve safety for the crew member, and conform to operations with new space vehicles.⁴ The Artemis generation will visit the lunar south pole, work in cis-lunar orbit, and explore further destinations in the solar system. Spacewalking, Moon walking, and eventually Mars walking enables human exploration. To this end, EVA spacesuit technology advancement will continue.

NASA has been pursuing in-house advanced suit development at JSC for the last 15 years culminating into the xEMU, now known as the government furnished equipment (GFE) design. While much is new, the xEMU architecture represents the best combination of elements from previous suit designs, both prototypes and flight implementations along with overcoming shortcomings of previous designs.

In 2021, the Agency implemented a strategy to commercialize spacesuit services.⁴ As the Artemis campaign matured with the award of the Human Landing System (HLS), coupled with the recent successes in the Commercial Cargo and Crew programs, a new procurement strategy was envisioned for Exploration EVA. This Exploration EVA Services (xEVAS) contract would provide an International Space Station (ISS) EMU spacesuit replacement and an Artemis lunar spacesuit. The selected vendor(s) would wholly develop, certify, and own the spacesuit. The contract would operate similar to how commercial crew vendors provide a launch (Commercial Crew Program contract) and ISS ferry service (Commercial Resupply Services contract). The vendors are responsible for the spacesuit design and fabrication and maintain ownership of the hardware. Under the xEVAS contract, NASA would make available the xEMU reference design, NASA's testing facilities, and NASA's xEMU personnel for the vendor to use and leverage how they deem appropriate to meet technical and deliverable requirements.

In 2022, the government awarded the xEVAS contract to two vendors; Axiom Space and Collins Aerospace.⁴ Axiom Space was issued a task order to deliver the EVA system for the Artemis III mission and Collins Aerospace was issued a task order to develop an EVA system for the ISS and complete a Critical Design Review in pursuit of that mission. The contract was written to add vendors as desired. NASA's Advanced Suit Team supported both task orders through mechanisms identified in the xEVAS contract.

The technology development and detailed design to enable the sustaining class lunar missions, as well as later missions to Mars, are still under NASA's purview and responsibility. For EVA, a sustaining class lunar mission is one that reuses the spacesuit for multiple missions. Furthermore, given the maturing design of the xEVAS vendors, clearly defined infusion paths are important to ensure that NASA technology investments can be leveraged in future flight designs for these later missions. It is within this context that EC5, in collaboration with the EHP TI&P Office, developed and continues to nurture EVA technology roadmaps for the Pressure Garment System (PGS) and Portable Life Support System (PLSS).

III. Extravehicular Activity Roadmaps

The EVA roadmaps' goals are to enable EVA operations on Mars using lunar surface opportunities for demonstration as appropriate, to facilitate risk mitigation for "sustained lunar" mission phase, and to increase life robustness for long-duration lunar missions. History has demonstrated that development of an exploration class lunar EVA spacesuit takes years; it is presumed that the same will be true for a Mars exploration EVA spacesuit. The progression of flight demonstrations from ISS, to boots on the Moon, to sustained lunar missions will serve as precursors and lessons learned for Mars missions. It is further expected that investments in Mars-enabling capabilities can improve lunar EVA performance. The Mars EVA spacesuit system will require a multitude of functions such as protection from the environment and mobility features.² Technology development will be needed to meet these requirements and many others.

An EVA spacesuit is an integrated spacecraft for a single person and typically consists of a PGS, a PLSS, and an informatics system. The EVA roadmaps in this paper are segmented into PGS and PLSS roadmaps. The informatics roadmap will be documented separately. Roadmaps serve as a means to identify and communicate capability gaps and the strategy for closing such gaps to accomplish mission objectives by reducing program and project risks. Each EVA roadmap is organized by capability gap (or group of gaps), follows a fiscal year (FY) timeline, and documents any additional information on key performance parameters, milestones, decision points, or important details. The PGS and PLSS roadmaps are designed based on a Gantt chart style, using icon shapes and sizes to represent details such as funding status, funding source, and duration. The tips for reading the roadmaps are shown in Figure 1.

A. Environment

Surface EVA exploration is significantly different from microgravity EVAs. The challenges include dust mitigation, operation in partial gravity, mobility and habitation considerations, site planning, and contingency

scenarios. Surface EVAs are faced with limitations to mass, power, volume, the environment, and physical operations that occur on the Moon and, to even greater extent, on Mars.⁶

The primary function of the EVA spacesuit system is to protect the crew member from the various environments encountered during a sustained lunar mission and a Mars mission, independent of a pressurized cabin. A surface EVA spacesuit must provide sufficient safety, mobility, communications, and comfort for crew to perform in an airlock or outside a vehicle for up to a full workday.²

The Mars EVA spacesuit, intended for Martian surface operations, will be different from a lunar spacesuit. The Mars spacesuit will be unique because of gravity and environmental differences and planetary protection strategies. Martian gravity is higher than on the Moon. The resulting increased weight calls for improved mobility and system mass reductions. The thin Martian atmosphere and the predominance of carbon dioxide (CO₂) in the atmosphere will require changes in life support system operation.²

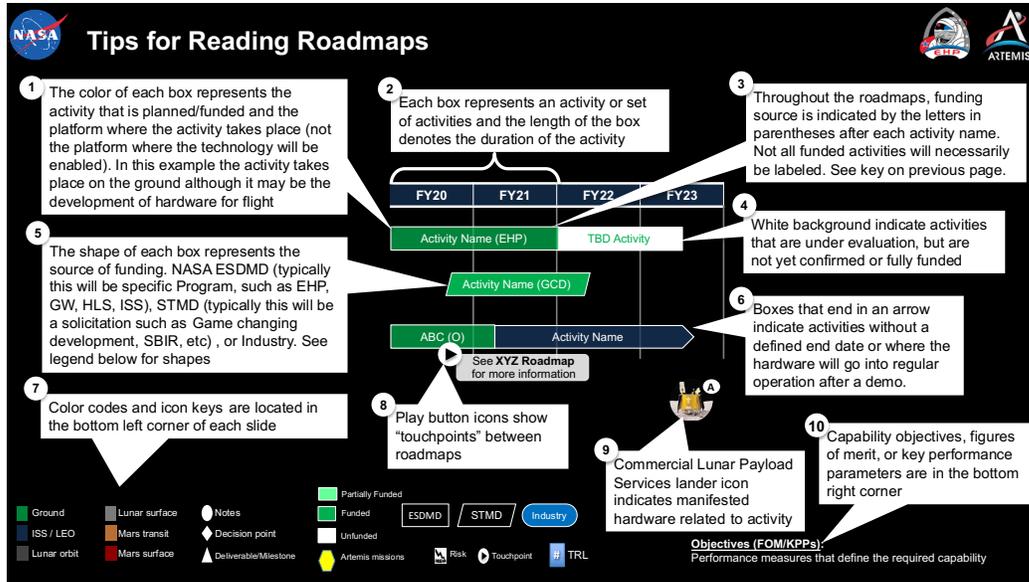


Figure 1. Tips for reading roadmaps

B. Assumptions

The ESDMD Moon-to-Mars ADD document² was used as a primary reference for the development of the EVA Technology Roadmap. Additionally, a Mars schematic study was conducted in FY24 (See Figure 7) and the majority of the assumptions for the EVA Technology Roadmap were extracted from that study. The assumptions are as follows:

1) Martian atmosphere 95% CO₂ at ~0.15 psia; 2) Martian gravity is 0.38g compared to Lunar gravity of 0.16g; 3) Long travel and mission duration; 4) Conditions of dust is a major hazard; 5) Martian radiation environment is a major hazard; 6) Mars has a unique seasonal environment; 7) Planetary protection may drive reduced suit leakage and compatibility with system-level bio-cleaning procedures; and 8) Suitport and commonality with a vehicle system is not considered for this Roadmap. Global Variables were also considered and are shown in Figure 2.

Average Metabolic Rate:	350 W (1194 BTU/hr)
Maximum Metabolic Rate:	530 W (1810 BTU/hr)
Suit Pressure:	4.3 psia
Inner Suit Temperature:	294.3 K
EVA Duration:	8 hours
Maximum Equipment Use Duration:	10 hours
Mass Package Factor:	2.2
Number of EVAs Assumed:	100

Figure 2. Global Variables

C. Pressure Garment System Roadmap

The xEMU project and subsequently the Exploration Pressure Garment System (xPGS) evolved over time. In 2018, the xEMU demonstration pressure garment architecture was released, which included a new Hard Upper Torso, Shoulders, Helmet, and Extra-Vehicular Visor Assembly (EVVA), while reusing the EMU lower torso, arms, gloves, and boots. The xEMU demo project covered the manufacturing of a PLSS and PGS. The project's intent was to conduct a flight demonstration of new technologies on the ISS and then transition fleet manufacturing and sustaining to a prime contractor to replace the EMU.

However, with the direction in 2019 to accelerate a lunar landing by the mid-2020s, the xEMU project was identified as the best path to manufacture spacesuits for the initial lunar mission, projected to occur near the lunar

south pole. As a result, the xEMU project transitioned into a multiple-program flight project that included development of both a spacesuit for the ISS and for the first Artemis lunar surface mission. This transition to a multi-program, multi-destination system was a significant change in project scope and requirements that resulted in changes to the xPGS's architecture. These changes included improved lower torso mobility, lunar boots that meet challenging thermal requirements of the permanently shadowed regions of the Moon, a new environmental protection garment (EPG) for dust protection, and enhanced cycle life performance over the needs of the ISS. The xPGS design verification testing unit, the pressure garment of the xEMU is shown in Figure 3. For much more detail on the design of the xPGS and its components, refer to the various manuscripts published in International Conference on Environmental Systems (ICES) 2022. The PGS roadmap is divided into Mars-enabling and sustaining lunar technologies along with the detail on the investments.

1. Scope of Mars vs. Sustaining Lunar

The PGS roadmap has two primary technical mission scopes. The first scope is Mars, which identifies and maps Mars-enabling technologies that may not or will not be completed as part of a sustaining lunar EVA spacesuit architecture. For example, given the unique thermal environment of Mars, a large emphasis of the Mars roadmap is Mars-specific thermal insulation and integration into a Mars EPG. The second scope is Sustaining Lunar, which identifies and maps technologies that are required to enable sustaining-class Artemis missions. For example, long-term durability, cycle life and maintainability are all aspects of an EVA spacesuit that enable sustaining mission profiles on the Lunar surface.

One aspect of exploration pressure garment design is that there is significant overlap between sustaining lunar and Mars. Despite differences in dust morphology, gravity, thermal environment, and operational concepts, much of the underlying design drivers are the same as they relate to pressurized mobility and comfort, durability, cycle life, and maintainability. The structure of the roadmap is designed to accommodate this overlap and communicate the technology development needs more clearly and logically.

As shown in Figure 4, the overlapping area illustrates the significant quantity of Mars capability needs that will enhance lunar exploration.

2. PGS Roadmap

The PGS roadmap is displayed in Figure 5 and Figure 6. The Mars Roadmap in Figure 5 emphasizes the need for architectural maturation, improved durability and maintainability of design, and development and integration of a unique Mars thermal solution.

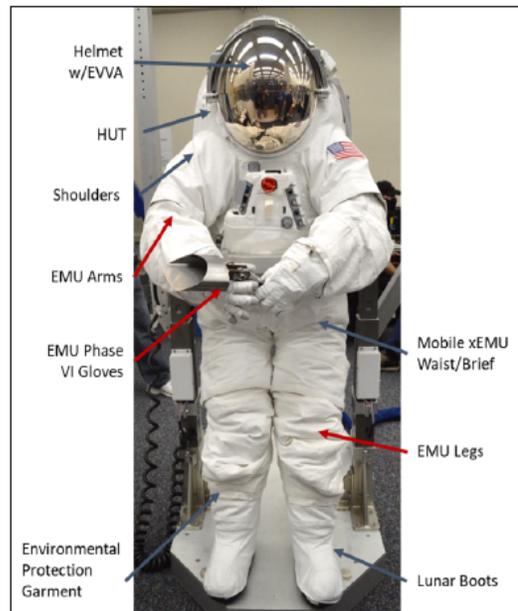


Figure 3. xPGS assembly

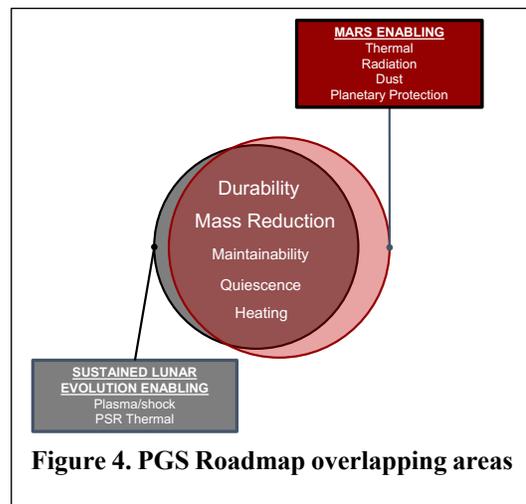


Figure 4. PGS Roadmap overlapping areas

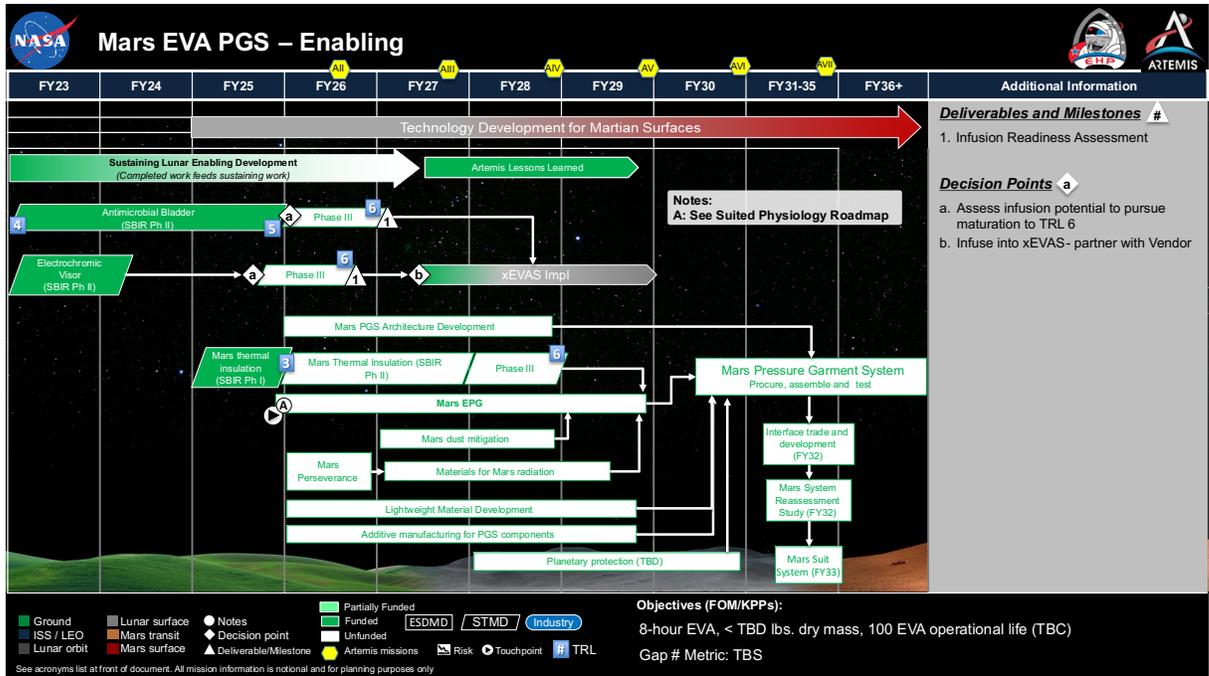


Figure 5. Mars EVA PGS –Enabling Roadmap

a) NASA Funded “Mars EVA PGS – Enabling” Investments

- **Antimicrobial Bladder** – Optimize urethane coatings for anti-microbial performance while not undermining other characteristics of suit bladder materials. Vendor is working with an xEVAS vendor partner and will deliver full EMU arm segments to NASA for future testing. (TRI-Austin)
- **Mars Thermal Insulation** – Develop next generation insulation materials for a Mars EVA suit in the CO₂ atmospheric environment. Vendors are providing samples to NASA and may be considered for a Phase II.

b) Proposed Activities: “Mars EVA PGS – Enabling”

- **Mars Perseverance** – Complete ground test unit for the Mars 2020 Perseverance Rover Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals instrument.
- **Mars PGS Architecture Development** – Conduct analysis, prototyping and testing to mature definition of the Mars PGS architecture.
- **Mars EPG** – Incorporation of Mars-optimized outer materials with Mars thermal insulation into a full EPG assembly, which can be evaluated with a PGS for thermal, cycling and mobility performance.
- **Mars PGS** – Incorporate Mars EPG and other Mars investments into a full PGS to evaluate and assess against Mars requirements.
- **Mars Suit System** – Mars System Reassessment Study informs Mars Suit System Acquisition Strategy.
- **Lightweight Material Development** – Maturation of lightweight composites or other materials that reduce PGS system mass to enable acceptable performance in Mars gravity.
- **Additive Manufacturing for PGS components** – Additive manufacturing capability for PGS parts would significantly reduce cost for both flight and prototype fabrication. It also enhances EVA system maintainability, improves EVA system sizing schemes, and reduces total EVA system mass for a sustaining architecture by reducing sparing needs.
- **Materials for Mars Radiation** – The long-term performance of suit materials exposed to the Mars radiation environment is unknown. Unique materials for the Mars EPG may be required which involve significant investment.
- **Planetary Protection** – Agency priorities, risk posture and requirements are currently unknown. However, it is expected that this area may drive reduced suit leakage and/or compatibility with system-level bio-cleaning procedures.

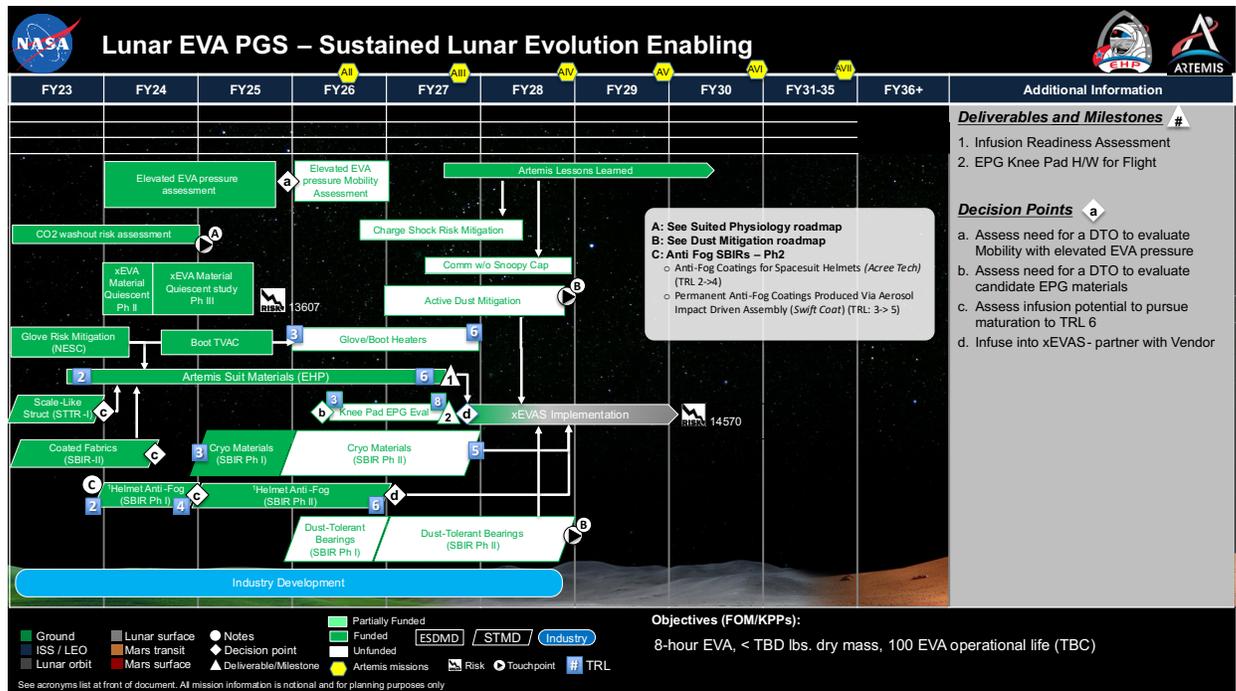


Figure 6. Lunar EVA PGS – Sustained Enabling Roadmap

c) NASA-Funded “Lunar EVA PGS – Sustained Lunar Evolution Enabling” Investments

- **CO₂ Washout Risk Assessment** – Three-phased approach to update the suited CO₂ washout methodology following NASA Engineering and Safety Center (NESC) findings/recommendations. Re-assessment and re-design of the suited CO₂ washout test setup and methodology with joint NASA-external subject matter expert team and oversight by Office of the Chief Health and Medical Officer-led Standing Review Panel.
- **Glove Risk Mitigation** – Lunar Glove Thermal and Durability Analysis, Test, and Failure Mitigation. Develop consistent/standardized testing defined to evaluate durability of existing glove for Lunar surface to baseline Lunar performance data on the Phase VI gloves from which to compare new design and evaluate material characteristics of candidate Lunar EPG materials.
- **Artemis Suit Materials** – Develop several EPG material solutions that can be used to mitigate the near-term robustness risks of the xEVAS vendor suit and gloves not being designed for sustained lunar EVAs. This development includes unique evaluation of several concepts to increase material robustness including, but not limited to new fiber, yarns, and fabric constructions, and fabrication.
- **Scale-Like Structures** – Evaluate feasibility of scale-like structures for lunar durability. (North Carolina State/Paragon)
- **Coated Fabrics** – Develop and evaluate coated fabrics suitable as EPG outer shell materials (Force Engineering).
- **Helmet Anti-Fog** – Two vendors are currently working on a Phase II to optimize a durable, effective permanent anti-fog treatment for exploration helmet architectures.
- **Boot Thermal Vacuum (TVAC)** – The xEMU boot is being tested at cryogenic temperatures at vacuum to develop the testing capability for xEVAS vendors, and to refine the Lunar EVA thermal model.

d) Proposed Activities: “Lunar EVA PGS – Sustained Lunar Evolution Enabling”

- **Elevated EVA pressure Mobility Assessment** – Perform an Elevated EVA pressure Mobility Assessment Developmental Test Objective (DTO) to assess mobility impacts on the lunar surface due to elevated EVA pressure. Limited data is available on exploration and decompression sickness treatment atmosphere cycle life and mobility performance of PGS components. Assessment of xEMU and other PGS component cycling performance at elevated EVA pressures will inform sustaining mission design maturation and highlight key deficit areas where attention is required to meet current or future requirements.
- **Knee Pad EPG Eval** – Propose to fly a removable knee pad EPG solution(s) Detailed Test Objective on Artemis III to evaluate candidate sustaining lunar fabrics and wear mitigation solutions.

- **PGS Charge/Shock Risk Mitigation** – Mature characterization of charge/shock risk to EVA and pursue risk mitigation activities.
- **Communication (i) without (w/o) Snoopy** – Intra-helmet audio system that eliminates the need for “snoopy cap” worn inside the helmet.
- **Glove/Boot Heaters** – Develop high efficiency, distributed heat glove and boot heater elements to close thermal gap in lunar permanently shadowed regions.
- **Dust Tolerant Bearings** – In partnership with the Dust Mitigation projects development, mature PGS mobility element bearings that are tolerant or more resistant to dust intrusion without impacts to wear or mobility.
- **Cryo Materials** – Non-fabric materials for the PGS, such as adhesives, room-temperature vulcanizing materials, boot soles, etc.

D. Portable Life Support System Roadmap

A space suit PLSS is a highly integrated, tightly constrained, packaged assembly providing life support functions for the suited crew member. Primary life support functions does include: oxygen (O₂) storage and pressure regulation for breathing and environmental habitability; CO₂ washout and removal; trace contaminant control; and thermal control for the crew member and space suit avionics. There are numerous constraints to PLSS design, packaging, and space suit integration such as volume, on-back mass, center of gravity, front-to-back dimension, and accessibility of maintenance items, among other system performance requirements. The PLSS interfaces via umbilical with vehicle systems (ISS, lunar lander, rover) to recharge consumables, utilize a vehicle heat exchanger during intravehicular activity (IVA) operations, and access vacuum for CO₂ desorption while IVA.



Figure 7. xEMU PLSS

Figure 7 shows a rear perspective (looking at the suited crew member’s back) of the government reference design, the xEMU PLSS, shown without the xEMU PLSS impact shield and EPG. This image shows the primary and secondary oxygen assemblies on the right and left sides, respectively, two fans in the upper center, rapid cycle amine (RCA) in the center, Suit Water Membrane Evaporator (SWME) near the lower center, and the radio and informatics system at the bottom. The balance of the PLSS system is present but cannot be clearly discerned in this image.

The goal of the xEMU PLSS architecture was to enable an exploration-forward design for use in microgravity at the ISS and in lunar gravity on the Moon. The design targeted increased robustness and reliability, reduced consumables use, and improved maintainability at the operational destination. Technology upgrades will be required prior to a Martian mission to account for the atmosphere and increased gravity field, among other considerations. The PLSS roadmap addresses current PLSS technology risks as well as existing gaps in long duration lunar and Martian-ready capabilities. Due to the complexity of the hardware and technologies, the xEMU PLSS took approximately 20 years to progress from schematic, through component technology development, system integration, and maturation. Given that NASA is targeting human travel to Mars in the late 2030s, it is critical that the roadmap is used as a tool to communicate functional capability development needs as well as funding opportunities. The PLSS roadmap has been divided into four swim lanes: 1) Cross-Subsystem Development and System Architecture (Figure 8); 2) O₂ Supply and Ventilation (Figures 9a, 9b, and 9c); 3) Thermal Control (Figure 10); and 4) Avionics & Power (Figure 11).

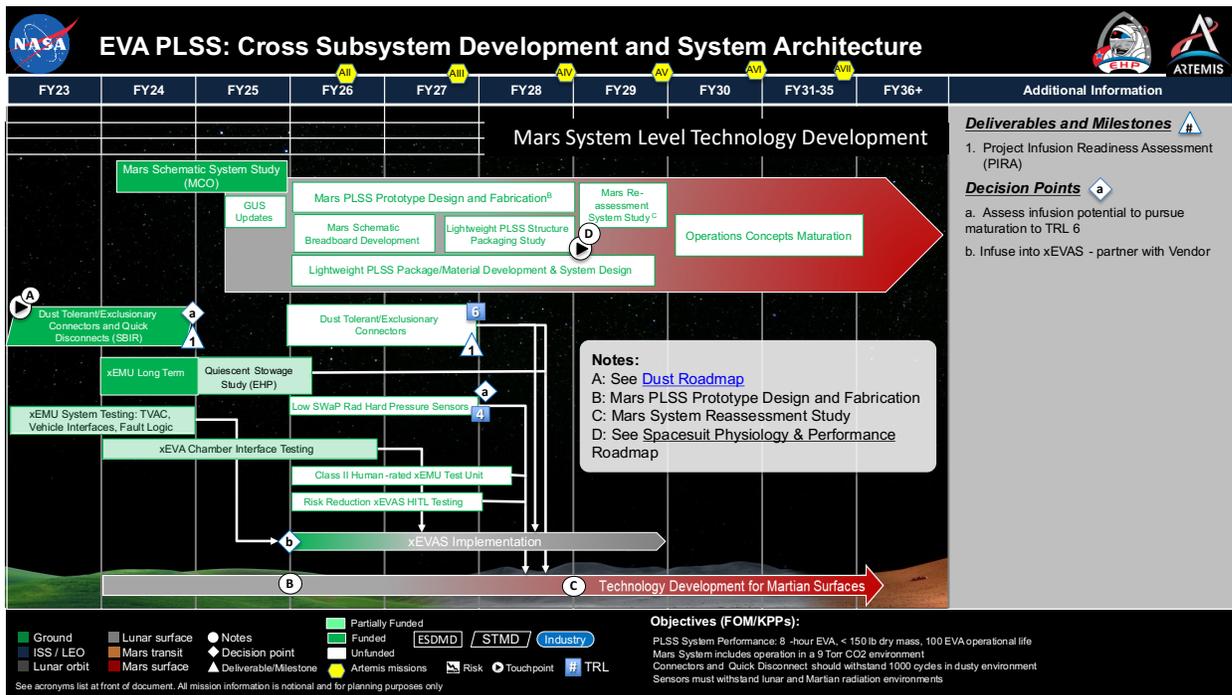


Figure 8. Cross Subsystem Development and System Architecture

1. Cross-Subsystem Development and System Architecture

These criteria either involve system integration or common components. As individual technologies are developed, a system architecture trade must be done to evaluate how they function as part of the larger life support system. Periodic system hardware demonstrations must be performed to fully assess the merits of specific technologies and system designs. The end goal is to focus on closing the gap of fully packaged, integrated, and functional PLSS.

a) NASA Funded “EVA PLSS: Cross Subsystem Development and System Architecture” Investments

- **Mars System Schematic Study** – This study will assess potential technologies for a Mars PLSS. Key changes from the xEMU include operation in a low-pressure CO₂ atmosphere and 1/3 gravity on Mars. The result of this study will be a set of technologies to pursue and a schematic of a Mars PLSS.
- **Dust Tolerant/Exclusionary Connectors and Quick Disconnects** – Connectors are needed (on the suit umbilical as an example) that are dust tolerant or exclusionary. Dust can cause jamming, leakage, or contamination for fluid or electrical connectors.
- **xEMU Long Term Quiescent Stowage Study** – Lunar storage requirements may exceed the originally anticipated requirements; assessments are needed to ensure that materials and system components will still meet requirements after an extended duration of storage at the Gateway or on the lunar surface. This work was fully funded in FY24, partially funded in FY25, and planned for funding in FY26.

b) Proposed Activities: “EVA PLSS: Cross Subsystem Development and System Architecture”

- **Mars Schematic Study** – Includes upgrades to the Guided Utility Sizer (GUS) and Mars Schematic Breadboard Development.
- **Low Size, Weight, and Power (SWaP) Rad Hard Pressure Sensors** – xEMU pressure sensors use an embedded circuit to amplify the output providing improved precision over existing state of the art. The next step in the evolution of these sensors is to develop a radiation-hardened version.
- **Lightweight PLSS Structure Packaging Study** – This study will assess on-back mass, center of gravity, fall protection, and best overall packaging.
- **Lightweight PLSS Structure Packaging Study/Material Development & System Design** – PLSS Mass Reduction | Current: 215 lbs., Goal: 132 lbs. (Apollo PLSS/Oxygen Purge System/Remote Control Unit). Analysis & Assessments of a lightweight PLSS Architecture Design. Materials Assessment for Infusion into current suit. Design prototype components utilizing advanced materials/processes/technology.
- **Mars PLSS Proto-type Design and Fabrication** – Mars PLSS Prototype Design and Fabrication: A system level test of the technologies selected in the Mars schematic study will be performed. This will likely be a breadboard style test article to demonstrate basic life support functionality.

- **Mars Re-assessment System Study** – After the first iteration of the Mars PLSS design, the system and technologies will be reassessed. This may be an opportunity to incorporate new technologies that have undergone new development since the original Mars PLSS schematic study.
- **Operations Concepts Maturation** – Operations Concepts Maturation: This will be a higher fidelity Mars PLSS. It will include technologies that have been matured through the previous development activities, will address system packaging, can begin to incorporate vehicle interfaces (if available), and can be an asset used to help mature Mars mission studies.
- **xEMU Integrated Testing Series** – Continued testing of the xEMU government baseline suit reduces risk for the xEVAS vendors.
- **xEMU System Testing TVAC, Vehicle Interfaces, Fault Logic** – xEMU thermal-vacuum testing completed in FY23. Additional testing with the Short xEMU can demonstrate additional aspects of the system performance including vehicle interface, fault logic with the Caution and Warning system or lower-level controllers, additional component performance mapping, and increase life cycles on the system.
- **Chamber Interface Testing** – The xEMU government suit can be used to demonstrate different test assets that will be available to the xEVAS vendors, such as the 11-foot chamber, Space Station Airlock Test Article, or Chamber B.
- **Class II Human-rated xEMU Test Unit** – This task would generate an O₂-rated xEMU that could be used in subsequent human-in-the-loop (HITL) tests.
- **Risk Reduction xEVAS HITL Testing** – HITL tests with the xEMU.

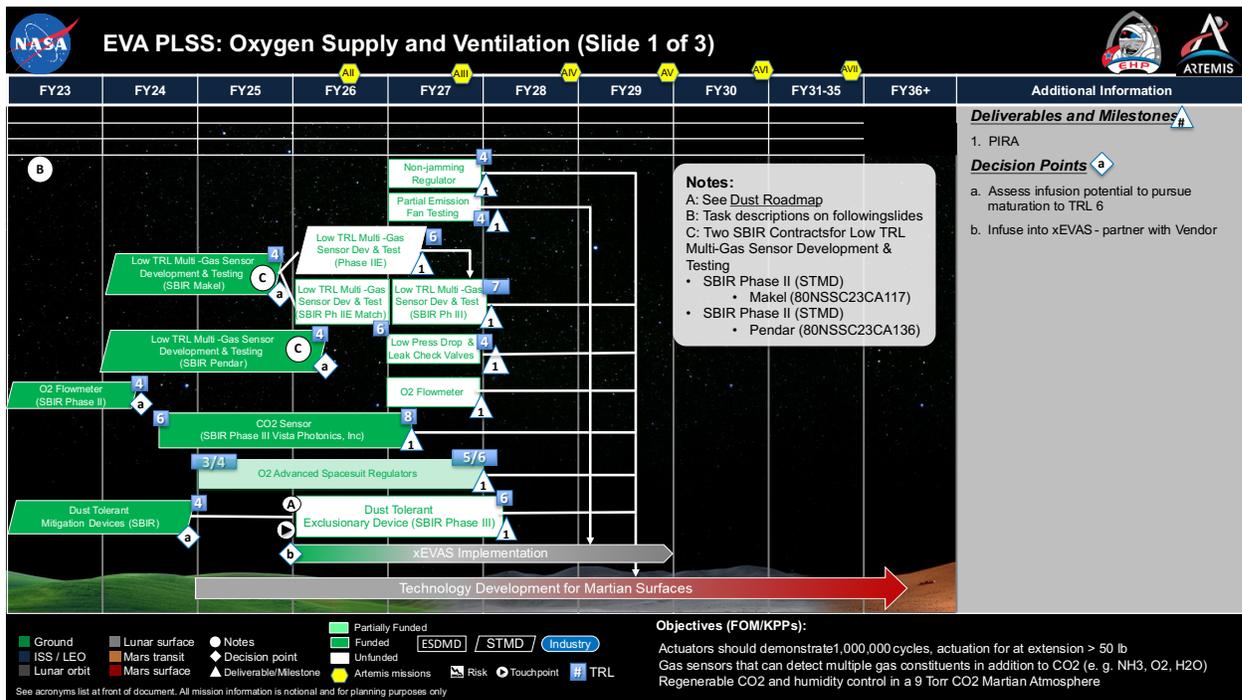


Figure 9a. Oxygen Supply and Ventilation (1 of 3)

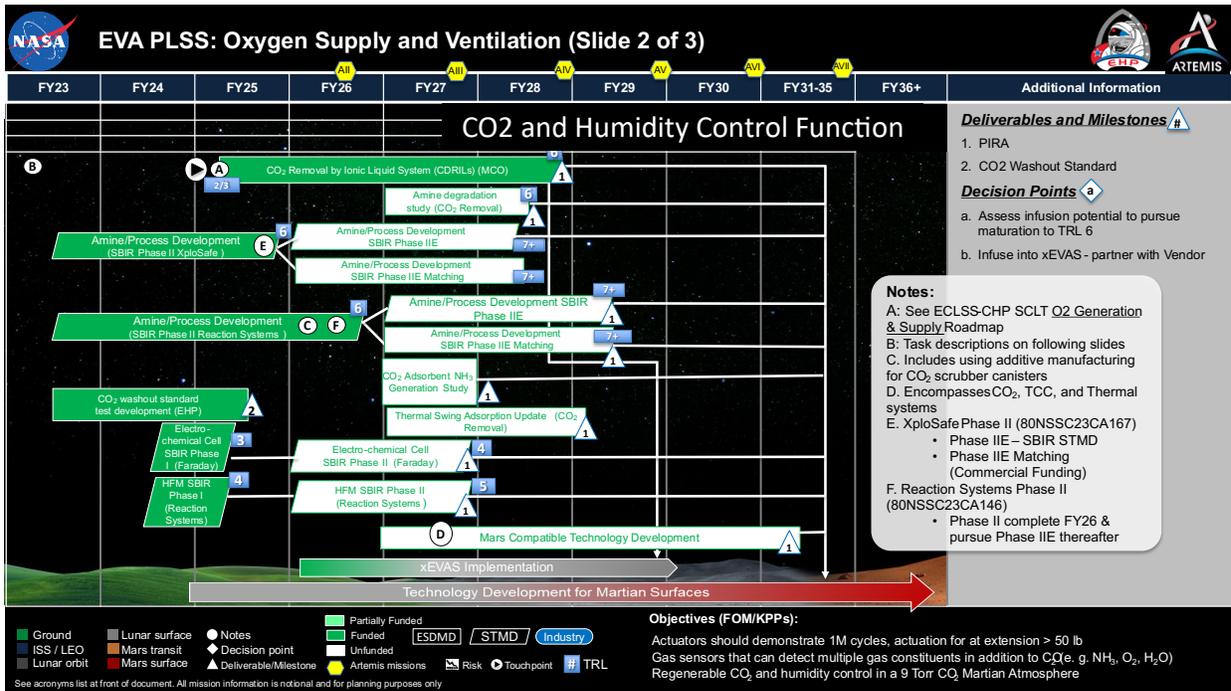


Figure 9b. Oxygen Supply and Ventilation (2 of 3)

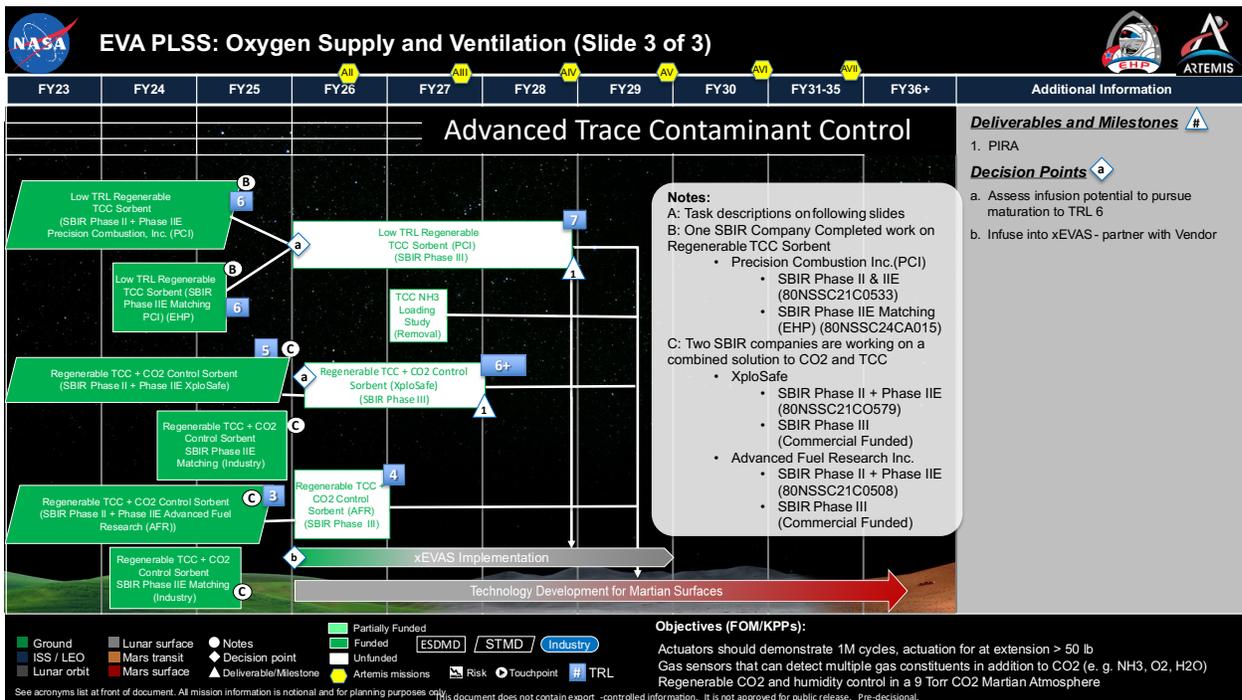


Figure 9c. Oxygen Supply and Ventilation (3 of 3)

2. O₂ Supply & Ventilation

The PLSS must store and provide O₂ to crew members at appropriate spacesuit pressures for the duration of an EVA. The PLSS must circulate O₂ through the spacesuit and remove constituents like CO₂, humidity, and trace contaminants.

a) NASA Funded “EVA PLSS: Oxygen Supply and Ventilation” Investments

- **Low Technology Readiness Level (TRL) Multi-Gas Sensor Development and Testing** – The current ISS-EMU and xEMU have CO₂ sensors to monitor conditions in the suit. Low TRL efforts have previously evaluated multi-constituent sensors that could also potentially measure humidity, O₂, or ammonia.
- **O₂ Flowmeter** – Low Pressure Drop Oxygen Flow meter for the PLSS. This is the completion of investment to develop a new concept for a ventilation loop flow meter.
- **Lunar Dust Mitigation Devices** – Small Business Innovative Research (SBIR) Phase II Contract with Innovation Aerospace, LLC to design Lunar Dust Mitigation Devices.
- **Amine/Process Development** – Nanoporous materials to provide CO₂ and Humidity control for the xEMU with minimal power requirements and low volume and mass. High-capacity RCA sorbents for increased cycle times.
- **CO₂ washout standard test development** – In order to manage the CO₂ inspired by an astronaut, the spacesuit must scrub the CO₂ from the life support system, but the flow in the helmet must also carry the exhaled gas away from their oro-nasal region. Quantifying wash out and inspired CO₂ has historically been difficult. Test results and computational fluid dynamics models are often hard to correlate. An improved, and then standardized methodology is needed to demonstrate acceptable CO₂ control, especially in this era of commercially provided suits.
- **Low TRL Regenerable Trace Contaminant Control (TCC) Sorbent** – TCC cartridges are consumables. If a regenerable technology could be developed it would decrease total EVA system mass and in-flight logistics. Vacuum-Regenerable TCC.
- **Regenerable TCC + CO₂ Control Sorbent** – If a CO₂ control sorbent could be developed that also captured trace contaminants, this could eliminate a component in the PLSS. Vacuum-Regenerable Sorbent System. Advanced Multipollutant Trace Contaminant Sorbents.
- **CO₂ & Humidity Control** – Two SBIR Phase I's were awarded to Faraday (Electrochemical Cell) and Reaction Systems (Hollow Fiber Membrane).
- **Carbon Dioxide Removal by Ionic Liquid System (CDRILS)** – CDRILS non-venting, CO₂/H₂O sequestration. CDRILS will utilize a small hollow-fiber membrane scrubber with a circulating liquid absorbent that would absorb CO₂ and humidity throughout the EVA and storing it. After the EVA, the ionic liquid will be circulated through the vehicle CDRILS system to recover the CO₂/H₂O and regenerate the ionic liquid. With modification, the vehicle CDRILS demonstration launching in 2028 could integrate the Mars EMU CDRILS and allow for demonstration of the technology for both applications.

b) Proposed Activities: “EVA PLSS: Oxygen Supply and Ventilation”

- **Non-jamming Regulator** – The xEMU used a common linear actuator to control multiple PLSS components. Actuator jamming was experienced often, making the applicable component inoperable. This task will look at alternative actuator designs for oxygen regulators with the goal of providing reliable operation.
- **Partial Emission Fan Testing** – This task would perform acceptance testing on fans purchased at the end of the xEMU project. This design offers the potential for low power requirements.
- **Dust Tolerant Exclusionary Device** – Dust tolerant exclusionary connection advancement to protect the xEMU Rapid Cycle Amine Beds from lunar, and potentially Martian Dust. This component must be located on the outside of the suit and will be exposed to the dusty environment on the Moon or Mars. Designs are needed that will not experience failures like leakage or sticking after operation in a dusty environment.
- **Low Press Drop and Leak Check Valves** – The xEMU added redundant, parallel, fans to the system design. This drove a new requirement for a check valve to prevent back-flow through the non-operating unit. Initial xEMU check valve designs did not meet pressure drop or leakage requirements, which put additional burden on the fans to provide the required flow through the helmet of the suit.
- **Hollow Fiber/Electrochemical/Thermal Swing Adsorption Update/Mars Compatible Technology Development** – Multiple alternate CO₂ and Humidity control development efforts are needed to address key risks and push these technologies forward. These include assessing additive manufacturing techniques to build the scrubber canisters, evaluating how the current state of the art sorbent (SA9T) degrades over time, and developing new sorbents. These can be short term technologies, like assessing the Thermal Swing Adsorption technology under test in the 4BedCO₂ payload on ISS for EVA application, that are applicable to sustained lunar missions or for Mars missions. Martian missions provide a new technical challenge because regenerable technologies must reject CO₂ into the CO₂ atmosphere on Mars. Mars technologies could be different sorbents, different regeneration methods, or potentially a

boost compressor on the scrubber regeneration line to drive CO₂ into the higher partial pressure environment. Mars technologies will also need to address planet protection, as appropriate.

- **CO₂ Adsorbent, Ammonia (NH₃) Generation Study & TCC/NH₃ Loading Study (Removal)** – The SA9T sorbent currently used as the state-of-the-art CO₂ control technology produces small amounts of ammonia when it reacts with water. This becomes a driving constituent in the sizing of a TCC cartridge. An ammonia generation study is needed. Additional evaluations of this generation rate could reduce the size or increase the duration of use for a TCC cartridge.
- **Amine/Process Development** – Nanoporous materials to provide CO₂ and Humidity control for the xEMU with minimal power requirements and low volume and mass (XploSafe, LLC). High-capacity RCA sorbents for increased cycle times (Reaction Systems, LLC).
- **O₂ Flowmeter** – Low pressure drop O₂ flowmeter is needed for the PLSS.

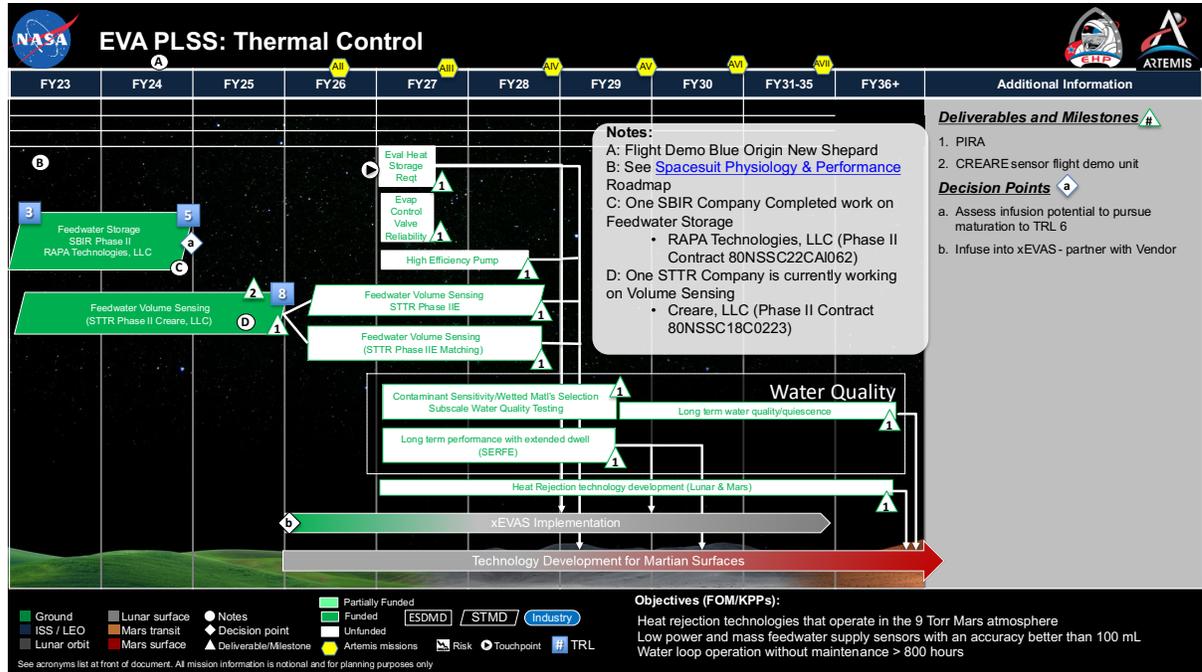


Figure 10. Thermal Control

3. Thermal Control

The PLSS provides cooling to the crew and spacesuit hardware. Development includes Liquid Cooling Garments, studies on long duration water and materials compatibility, heat rejection technologies that do not use consumables or can be used in a Martian environment, and thermal control valves.

a) NASA Funded “EVA PLSS: Thermal Control” Investments

- **Feedwater Storage** – Water is one of the primary consumables for a life support system that uses evaporation for cooling. A reliable, and gravity independent, technique for measuring the amount of water remaining is critical to monitoring the duration of an EVA. Volume Sensor for Flexible Fluid Reservoirs in Microgravity. Flight Demo on New Shepard launch, December 18, 2023. (Creare, LLC)
- **Feedwater Volume Sensing** – High-Purity, Defined-Envelope pressure Bladder. (RAPA Technologies, LLC)

b) Proposed Activities: “EVA PLSS: Thermal Control”

- **Evaluate Heat Storage Requirement** – Crew members generate variable amounts of heat during an EVA based on their activity levels. There are requirements for energy storage in the crew (as monitored by core body temperature) if their metabolic output exceeds the cooling capability of the life support system. Refinement of this requirement could enable sizing reductions for thermal control hardware.
- **Evaporator Control Valve Reliability** – The xEMU SWME uses a backpressure control valve to meter the water evaporation rate and thereby the cooling provided to the crew. The xEMU design experienced many issues with linear actuator reliability where the motor would jam, making the control valve inoperable. This task would look at designs that provide more reliable actuation while still meeting the flow rate and pressure drop requirements.
- **High Efficiency Pump** – Continued development and evaluations of water pumps with lower power requirements is desired.

- **Contaminant Sensitivity/Wetted Materials Selection Subscale Water Quality Testing/Long Term Water Quality and Quiescence/Long Term Performance with Extended Dwell** – Water quality issues have plagued the ISS EMU and other life support systems throughout NASA’s history. xEMU-based technology development efforts for SWME and the SWME Express Rack Flight Experiment (SERFE) ISS payload have taken large steps to demonstrate decreased sensitivity to water quality issues and improved materials compatibility as compared to previous systems. However, continued efforts are needed to completely reduce risks associated with water quality. These include sub-scale tests to assess materials or contaminants that might present performance issues to the current thermal control technologies; long term quiescent evaluations with the SERFE Ground Unit where it is tested after long dormant periods (> 2 years), and then additional long-term evaluations as the xEVAS designs are finalized and mission concepts mature.
- **Heat Rejection technology development (Lunar and Mars)** – The low-pressure CO₂ environment on Mars may degrade the performance of water evaporation-based technologies. In addition, non-venting heat rejection or storage technologies could decrease mission consumables. Low TRL heat rejection technologies need to be continually evaluated for potential benefits.
- **Feedwater Volume Sensing** – Continue development of the volume sensor for flexible fluid reservoirs in microgravity. (Creare, LLC). Flight demo on New Shepard, December 18, 2023, launch.

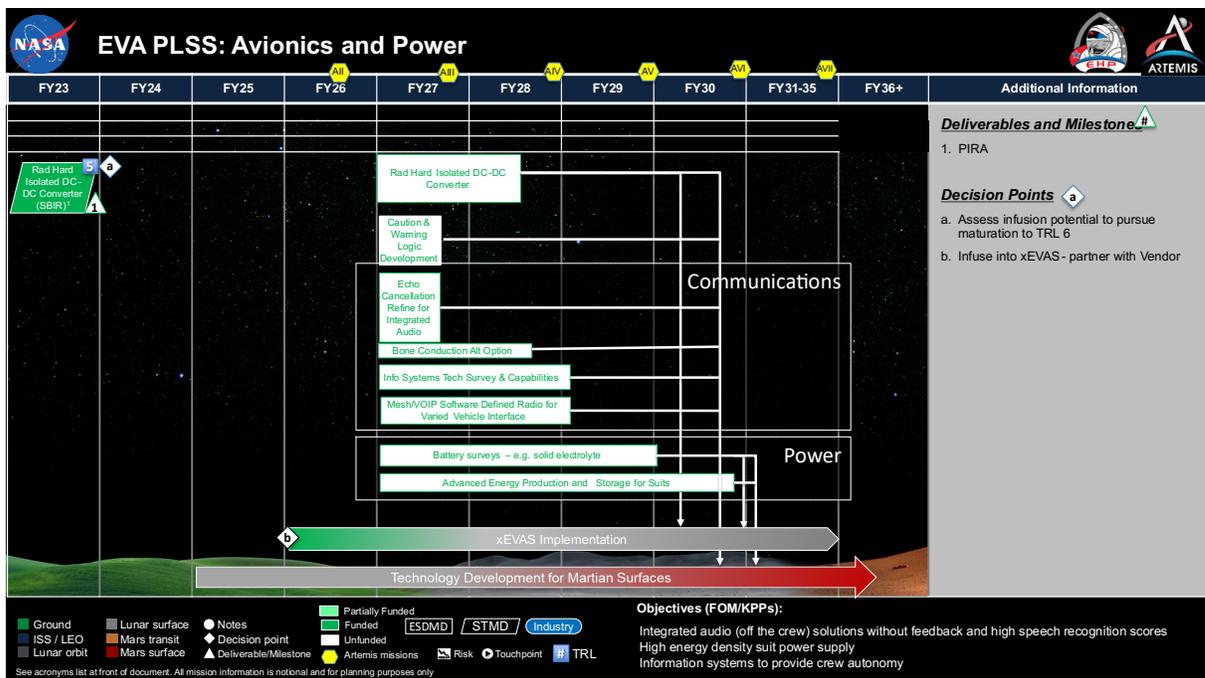


Figure 11. Avionics and Power

4. Avionics & Power

Radiation-hardened electrical and electronics engineering parts are needed to provide low volume, weight, and power avionics to distribute power, drive motors and actuators, read telemetry and provide spacesuit communication. Power to the PLSS is currently provided by batteries. Caution & warning, telemetry, and voice communication form a discipline and electronic ease of integration. However, for Mars application, these technical disciplines may not necessarily be integrated directly into the PLSS architecture.

a) NASA Funded “EVA PLSS: Avionics and Power” Investments

- **Radiation Hardened Isolated DC-DC Converter** – Self-calibrating, lightweight radiation hardened isolated Direct Current to Direct Current (DC-DC) converter. Radiation hardened electronic components typically lag in performance as compared to consumer electronics. This SBIR developed a radiation hardened DC-DC converter to distribute power inside of a PLSS controller. (Alphacore, Inc.)

b) Proposed Activities: “EVA PLSS: Thermal Control”

- **Radiation Hardened Isolated DC-DC Converter** – Self-calibrating, lightweight radiation hardened isolated DC-DC converter. Radiation hardened electronic components typically lag in performance as compared to consumer electronics.

- **Caution and Warning Logic Development** – This task can be performed as part of continued xEMU system level testing. xEMU testing has generally demonstrated life support functionality. Additional, evaluations can further develop and demonstrate the government baseline avionics and software design, especially in the areas of off-nominal operations or failure conditions.
- **Echo Cancellation Refinement for Integrated Audio** – The xEMU has significant risk with audio quality based on the design of integrating the microphones and speakers directly into the upper torso of the suit and not using a communications cap. This is especially critical once two suits are joined into the same loop. Risk reduction activities range from improved echo cancellation algorithms to improved acoustics inside of the helmet to speaker and microphone selection and placement.
- **Bone Conduction Microphone** – An alternative to current microphones could be an earpiece style microphone that converts vibrations in the user’s head into communication signals.
- **Information Systems** – The xEMU only developed the most basic information systems, including video and data streaming. Additional applications and hardware could range from heads up or wrist displays, to navigational tools, to electronic checklists. This is an area where continued development could enhance EVA efficiency and crew autonomy.
- **Mesh/Voice over Internet Protocol Software Defined Radio** – The ISS EMU and xEMU still rely on a radio frequency-based radio infra-structure. Future lunar networks are still being defined. A software defined radio with an internet protocol-based communication scheme is more representative of the current commercial state of the art in communication technologies.
- **Battery Survey** – Commercial battery applications drive technology at a much faster rate than the space industry. Continued assessment of emerging technologies for spacesuit applications can provide improvements in energy density, which translates to longer EVAs and less massive batteries.
- **Advanced Energy Production and Storage for Suits** – Spacesuits have always relied on batteries for power. Other technologies, potentially solar, thermal, fuel cells, or motion-based energy production should periodically be assessed and traded.

IV. Conclusion

The NASA Extravehicular Activity roadmaps serve to organize the significant scope of work in spacesuit technology development required to explore the Mars environment. As they are implemented, EVA roadmaps will provide enhancement to lunar mission capability as well. For each sub-system they provide a graphical view of the development path and, by implication, the method of infusing enabling technologies into flight hardware: first through schematic study and development, next in proof-of-concept breadboard early designs, then packaged into flight-like configurations, and finally integrated and tested in flight designs. As they are updated yearly, the roadmaps help spacesuit developers link nascent technologies with infusion targets and provide a condensed view of the schedule and funding needed for closing EVA suit capability gaps. The EVA roadmaps help to communicate NASA’s technology needs and intended priorities, which can highlight opportunities for collaborations across human spaceflight disciplines and with commercial or academic partners. It is the authors’ hope that these roadmaps will foster those kinds of collaborations.

EVA spacesuits symbolize human space exploration. Perhaps this is because the suits deliver explorers into their most intimate contact with the *Mundus Novus*⁷ they inhabit. EVA technology development is an iterative process where lessons learned through extensive testing are leveraged to integrate them into a wearable spacecraft that can be safely and reliably operated. The unique environments of Mars require the development of a new spacesuit configuration with technologies suitable for humans in that new world. The challenges of those environments tightly constrain design solutions. As 65 years of space suit development history have demonstrated, the time required to achieve successful, safe flight implementation in this constrained design space is on the order of a decade or more. The extravehicular roadmaps presented here will serve as a guide for future technology development and provide NASA’s programs and technical organizations with vital information as they make decisions on how to allocate resources and close technology gaps between now and future Mars missions.

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