NASA Extravehicular Activity Spacesuit Technology Roadmaps for Exploration — 2026 Status

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As 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. In 2025, NASA updated and expanded these EVA spacesuit technology roadmaps with more detail. 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 nearly two decades, 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 contracted with industry to procure EVA services through the Exploration EVA Services (xEVAS) contract. Services provided via the xEVAS contract include spacesuits, tools, equipment, vehicle interfaces, and support for training and real-time operations. NASA is focused on sustained human lunar surface exploration and a mission to Mars. NASA leadership has set goals and objectives related to the Agency's vision and a M2M strategy. This paper presents an update to the EVA Spacesuit technology roadmaps with alignment to NASA's vision.

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Nomenclature

ADD	=	Architecture Definition Document
AFR	=	Advanced Fuel Research
BTU/hr	=	British Thermal Unit per hour
CDRILS	=	Carbon Dioxide Removal by Ionic Liquid System
CO_2	=	carbon dioxide
Comm	=	communications
DC-DC	=	Direct Current
DTO	=	Developmental Test Objective
ECLSS	=	Environmental Control and Life Support Systems
EHP	=	EVA and Human Surface Mobility Program
EIO	=	Earth Independent Operations
EMU	=	Extravehicular Mobility Unit
EPG	=	environmental protection garment
ESDMD	=	Exploration Systems Development Mission Directorate
EVA	=	extravehicular activity
EVVA	=	Extra-Vehicular Visor Assembly
FOM	=	figures of merit
FY	=	Fiscal Year
g	=	Earth's gravity
GFE	=	government-furnished equipment
GUS	=	Guided Utility Sizer
GW	=	Gateway
H_2O	=	water
HFM	=	hollow fiber membrane
HITL	=	human-in-the-loop
HLS	=	Human Landing System
HUT	=	hard upper torso
ISS	=	International Space Station
IVA	=	intravehicular activity
JSC	=	Johnson Space Center
K	=	kelvin
KPP	=	key performance parameters
lbs	=	pounds
LEO	=	Low Earth Orbit
LIOH	=	lithium hydroxide
LTV	=	lunar terrain vehicle
MCO	=	Mars Campaign Office
ml	=	milliliter
M2M	=	Moon to Mars
NESC	=	NASA Engineering and Safety Center
NH_3	=	ammonia
O_2	=	oxygen
PCI	=	Precision Combustion Inc
PGS	=	Pressure Garment System
Ph	=	Phase
PLSS	=	Portable Life Support System
PR	=	pressurized rover
psia	=	pounds per square inch absolute
RCA	=	rapid cycle amine
SA9T	=	art sorbent
SBIR	=	Small Business Innovative Research
SCLT	=	Strategic Capabilities and Leadership Teams
SERFE	=	SWME Express Rack Flight Experiment
STIP	=	Strategic Space Technology Investment Plan
STMD	=	Space Technology Mission Directorate
STTR	=	Small Business Technology Transfer
SWME	=	Suit Water Membrane Evaporator
TBC	=	to be considered
TBD	=	to be determined
TBS	=	to be stated
TCC	=	trace contaminant control
TI&P	=	Technology Integration & Partnerships
TRL	=	Technology Readiness Level
TVAC	=	Thermal Vacuum
VI	=	six
VOIP	=	Voice over Internet Protocol
W	=	watt
w/o	=	without
xEMU	=	Exploration Extravehicular Mobility Unit
xEVAS	=	Exploration Extravehicular Activity Services
xPGS	=	Exploration Pressure Garment System

I. Introduction

THE work outlined in this paper is the culmination of nearly two decades of effort at National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC). The work has been planned and executed by the Space Suit and Crew Survival Systems Branch, which resides organizationally within the Crew and Thermal Systems Division within the Engineering Directorate at JSC. The effort has resulted in the design, development, assembly, and testing of the Exploration Extravehicular Mobility Unit (xEMU) advanced spacesuit government reference design. Over the last two years, the Branch has collaborated with the Technology Integration and Partnerships (TI&P) Office of the Extravehicular Activity and Human Surface Mobility Program (EHP). TI&P 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 to share the progress that NASA has made toward advanced spacesuit technology development in the form of roadmaps identifying EVA capability for future sustaining-class Artemis missions (Artemis VI+) as well as human exploration of Mars. In particular, this paper covers the maturation and development of spacesuit technology and updates the EVA technology roadmap for the M2M Program [1]. The EVA roadmap provides a visualization of an actionable plan to realize EVA technology capabilities needed for Mars and sustained lunar exploration. The roadmap is in alignment with both NASA's Exploration Architecture [2] and Civil Space Shortfalls [3] to meet future mission needs. Roadmaps facilitate discussion, decision making, and planning for programs and technical suppling organizations; they are not intended to accurately depict the details and statuses of the projects and tasks appearing within the plans. It is important to note that this roadmap and paper were prepared before the NASA Ignition Day event in March 2026 [4].

II. Historical Strategy

EVA spacesuit development has been ongoing since the very first spacewalk in 1965. The spacesuit and its associated systems have been changed to match the needs of each new mission, adapt to the destination environment, improve safety for the crew members, and conform to operations with new space vehicles [5]. The Artemis campaign will explore the lunar south pole, work in cislunar orbit, and visit further destinations in the solar system. Spacewalking, Moon walking, and eventually Mars walking enables human exploration. To achieve this goal, EVA spacesuit technology advancement must continue.

NASA in-house advanced suit development at JSC for the last 15 years culminated in the government reference xEMU design. The xEMU architecture overcomes shortcomings of the past, and implements the best elements of previously designed suits, prototypes and flight implementations.

In 2022, the Agency awarded a commercial spacesuit services contract [6]. To help create and sustain a presence on the Moon, NASA has contracted with industry to procure EVA services through the Exploration EVA Services (xEVAS) contract. Services provided via the xEVAS contract include spacesuits, tools, equipment, vehicle interfaces, and support for training and real-time operations. Under the xEVAS contract, NASA made available the xEMU reference design, testing facilities, and personnel for the vendor to use and leverage how they deem appropriate to meet technical and deliverable requirements. NASA's Advanced Suit Team supports through mechanisms identified in the xEVAS contract.

The technology development and detailed design to enable EVAs during the Sustained Lunar Evolution (SLE) phase, as well as missions to Mars, remain under NASA's purview. For EVA, a sustaining class lunar mission is one that reuses the spacesuit for multiple missions. Clearly defined infusion paths enable NASA technology investments to be leveraged in flight designs. It is within this context that NASA Engineering Directorate and EHP maintain EVA spacesuit technology roadmaps for exploration spacesuits.

III. Extravehicular Activity Spacesuit Technology Roadmaps

After launching and landing, an EVA or spacewalk is probably the next most difficult aspect of exploring space. A spacesuit designed for EVA is an integrated spacecraft for a single person. An EVA spacesuit is made up of a Pressure Garment System (PGS), a Portable Life Support System (PLSS), and an informatics system. In this paper, the EVA spacesuit technology roadmap is segmented into both the PGS and PLSS roadmaps and augmented by an integrated roadmap. The informatics roadmap is not covered in this paper and will be documented separately. The graphic in Figure 1 depicts the Exploration EMU (xEMU) government reference design. As a reference, Figure 1 provides a depiction of the PGS (left), a depiction of the PLSS without a back cover (middle), and PLSS detailed (right). The xEMU government reference design took years to design, develop, test, and evaluate due to technology innovation necessary to meet the goals and objectives. Likewise, it will take years to perform a similar effort for a Mars exploration EVA spacesuit.

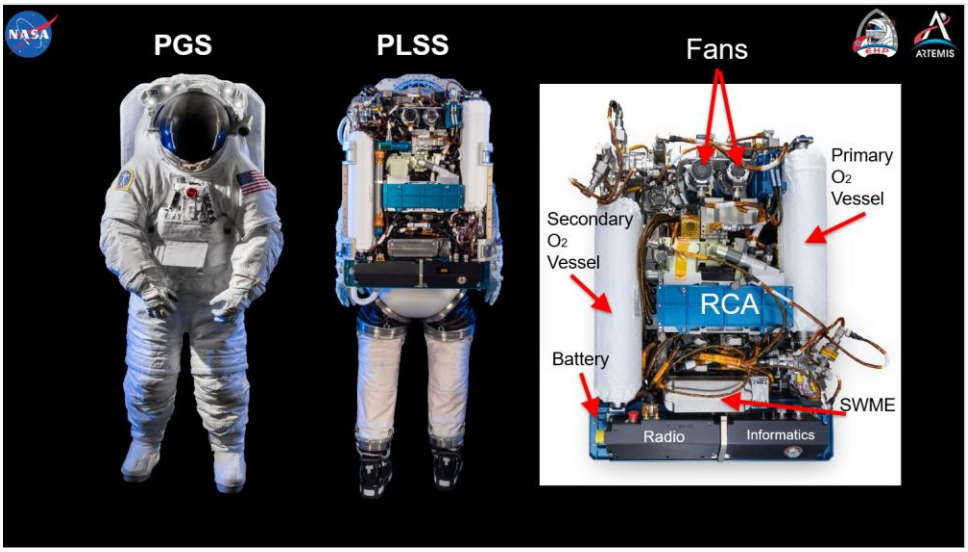


Figure 1. xEMU showing front left (PGS), back middle (PLSS), right (PLSS Detailed).

The EVA spacesuit technology roadmaps discussed in this paper are targeted 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. The technological progression along with flight demonstrations, to boots on the Moon, to sustained lunar missions will serve as precursors and lessons learned for Mars missions. Mars-enabling capabilities will take time. However, those capabilities can improve lunar EVA performance. The Mars EVA spacesuit system will require a multitude of functions and technology development to meet requirements [2].

Roadmaps serve to identify and communicate capability gaps and the strategy for closing such gaps to accomplish mission objectives. The EVA spacesuit technology roadmaps are organized by technical categories and follows a fiscal year (FY) timeline, and other important details. The PGS, PLSS, and integrated 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 2.

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 [7].

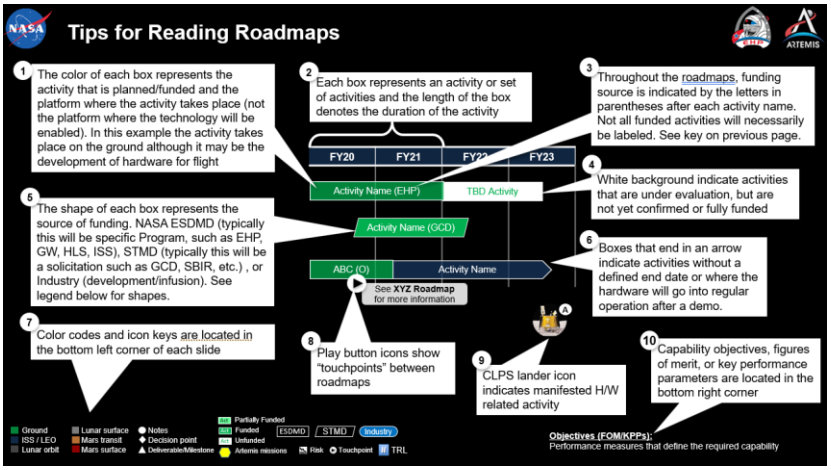


Figure 2. Tips for reading roadmaps.

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 (CO_2) in the atmosphere will require changes in life support system operation [2].

B. Assumptions

The ESDMD Moon-to-Mars ADD document [2] was used as a primary reference for the development of the EVA Spacesuit Technology Roadmap. Additionally, a Mars schematic study was conducted in FY 2024 and the majority of the assumptions for the EVA Technology Roadmap were extracted from that study [8]. The assumptions are as follows: 1) Martian atmosphere 95% CO_2 at ~0.15 psia; 2) Martian gravity is 0.38g; 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 are not considered for this Roadmap. Global Variables were also considered and are shown in Table 1. Packaging factor represents the mass of the suit structure compared to active components. A lower number represents requirements for a more integrated suit to lower overall mass.

Table 1. Global Varibles

Variables	Lunar/LEO	Mars
Average Metabolic Rate:	350W (1200 BTU/hr)	
Maximum Metabolic Rate:	880W (3000 BTU/hr)	
Suit Pressure:	4.3 psia	
Inner Suit Temperature:	294 K	
EVA Duration:	8 hours	4 hours
Maximum Equipment Use Duration:	10 hours	8 hours
Mass Package Factor:	2.2	1.7
Number of EVAs Assumed:	100	25

C. Pressure Garment System Roadmap

As outlined in previous versions of the EVA roadmap, the PGS roadmap is organized into two segments: Mars-enabling and sustaining lunar-enabling, along with associated investment details. Because many requirements, such as pressurized mobility, comfort, durability, cycle life, and maintainability are common to both sustaining lunar and Mars missions, the roadmap structure is designed to reflect this overlap and present technological development needs in a logical, transparent way regardless of mission applicability.

However, the significant on-back mass constraints for a Mars suit, compared to one used in lunar gravity, drive major architectural and design changes. These changes are still influenced by the same common design drivers. To improve clarity and logic, the roadmaps are decoupled from each other, and expanded to include all relevant activities for each mission context.

- **Mars PGS Roadmap:** Focuses on technologies that enable Mars missions and address current gaps. This revision places greater emphasis on defining the Mars PGS architecture and design to meet strict mass requirements. It also highlights solutions for Mars' unique thermal environment, prioritizing thermal insulation and integration into a Mars Environmental Protection Garment (EPG).
- **Sustaining Lunar Roadmap:** Identifies technologies needed for sustaining-class Artemis missions, such as long-term durability, cycle life, and maintainability, critical for extended lunar surface operations.

As shown in Figure 3 and discussed previously, there is still significant overlap with Mars capabilities also benefiting Sustaining Lunar, and vice versa. Even though the two roadmaps now stand alone, progress on one roadmap may reduce or eliminate work on the other, depending on specific requirements.

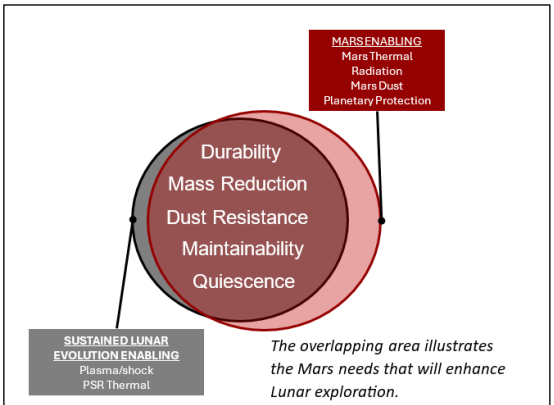


Figure 3. PGS Roadmap overlapping areas.

The PGS roadmap is presented in Figures 4 and 5.

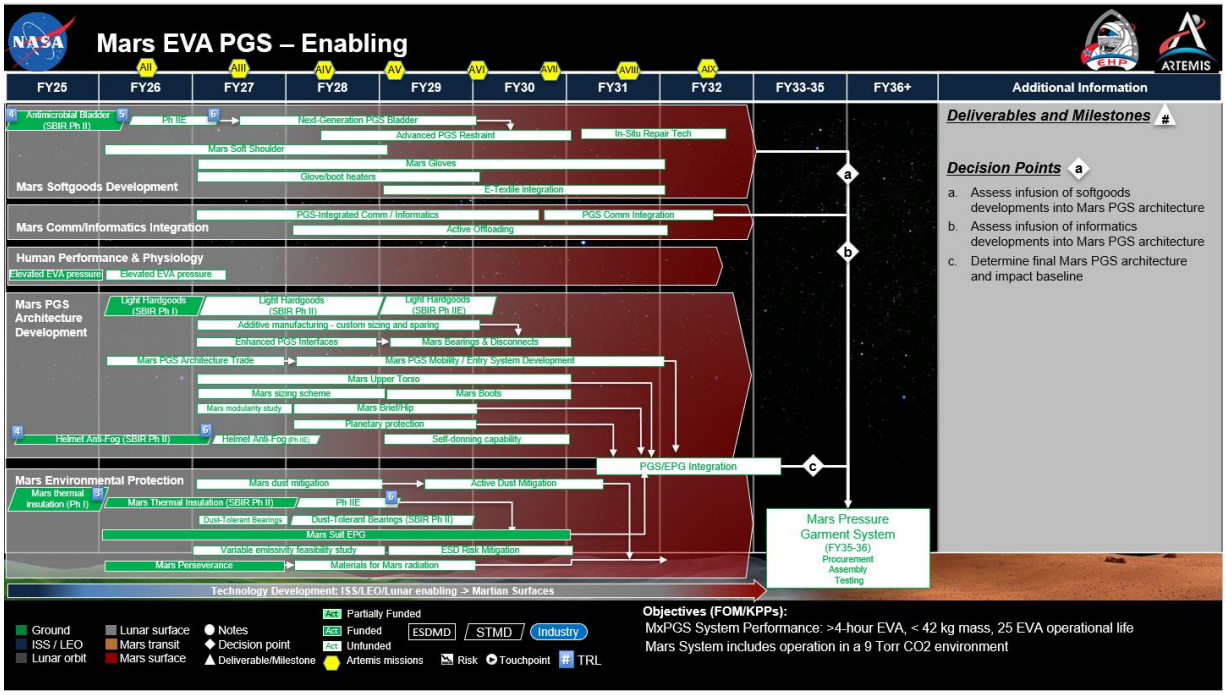


Figure 4. Mars EVA PGS – Enabling Roadmap.

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 CO_2 atmospheric environment. Vendors are providing samples to NASA and may be considered for Phase II
- **Mars Suit EPG** – Develop Mars Suit EPG, including layup material development (thermal insulation, outer shell, liner), patterning, and suit integration/testing
- **Mars Perseverance** – Irradiate and test, on the ground, suit materials that are currently on the Mars 2020 Perseverance rover SHERLOC instrument, to understand degradation in the Mars environment

b) *Proposed Activities: "Mars EVA PGS – Enabling"*

- **Mars Soft Shoulder –** Develop high performance soft shoulder design to meet Mars requirements
- **Mars Gloves –** Develop next generation Mars EVA glove
- **Mars PGS Architecture Trade** – Conduct initial PGS architecture trade to baseline architecture and inform subsequent development
- **Light Hardgoods** – Maturation of lightweight composites or other materials
- **Additive Manufacturing** – Inform bearings, disconnects, sizing features and bracketry as well as sparing strategy
- **Materials for Mars Radiation** – Develop materials and layup schemes to provide radiation resistance in Mars environment
- **Planetary Protection (TBD)** – Agency priorities, risk posture and requirements currently unknown; task is marked TBD.
- **Next Generation PGS Bladder** – Mature advanced bladder with enhanced capability for Mars (anti-microbial, etc.)
- **Advanced PGS Restraint** – Develop / baseline Mars restraint materials
- **Glove/boot heaters** – Heaters to address anticipated crew skin temperature challenges at the hand and foot during Mars EVA
- **E-Textile Integration** – Investigate feasibility of incorporating E-Textiles to PGS suit materials for dust resistance, sensing, etc.
- **PGS-Integrated Comm/Informatics** – Mature PGS/informatics integration, such as integrated communication with noise canceling, HUD, etc.
- **In-Situ Repair Tech** – Investigate opportunities for in-field PGS repair, including self-healing and patch kits
- **Active Offloading** – Investigate feasibility of incorporating active offloading to PGS to support EVA operations
- **Enhanced PGS Interfaces –** Mature the PGS/PLSS interface.
- **Mars Bearings and Disconnects** – Develop bearings and disconnects for Mars that provide enhanced performance and/or reduced mass
- **Mars PGS Mobility/Entry Dev** – Mature the PGS mobility and entry architecture/geometry, and detailed design
- **Mars Upper Torso** – Develop a lightweight Mars upper torso design based on the selected Mars PGS architecture
- **Mars Sizing** – Develop a Mars PGS sizing scheme and design sizing elements/features
- **Mars Modularity** – Investigate trade of modularity in Mars PGS design given architecture and currently known DRMs
- **Mars Boots** – High-performance Mars boot based on lessons learned and incorporating best practices of footwear design
- **Mars Brief/Hip** – Mars Brief/Hip architecture and design based on the selected Mars PGS architecture
- **Helmet Anti-Fog** – Mature development and testing of integrated permanent helmet anti-fog
- **Self-donning –** Investigate features for, and validate, self-donning capability of the Mars PGS
- **Mars Dust Mitigation** – Investigate technologies, designs and features to mitigate dust susceptibility of the Mars PGS
- **Dust-tolerant Bearings –** Develop bearings that are more tolerant to dust and/or easier to maintain in dusty environment

- **Active Dust mitigation** – Investigate feasibility of incorporating active dust mitigation into the PGS EPG.
- **PGS/EPG Integration** – Design and fabricate a Mars EPG that is optimized for the selected Mars PGS architecture
- **ESD Risk Mitigation** – Investigate need and opportunities for mitigating risk of ESD
- **Variable Emissivity Feasibility Study –** Investigate feasibility of variable emissivity coatings to provide Mars suit thermal control
- **Mars Suit Assembly/Test –** Incorporate all Mars development work into a final suit that is procured (as needed), assembled, and tested

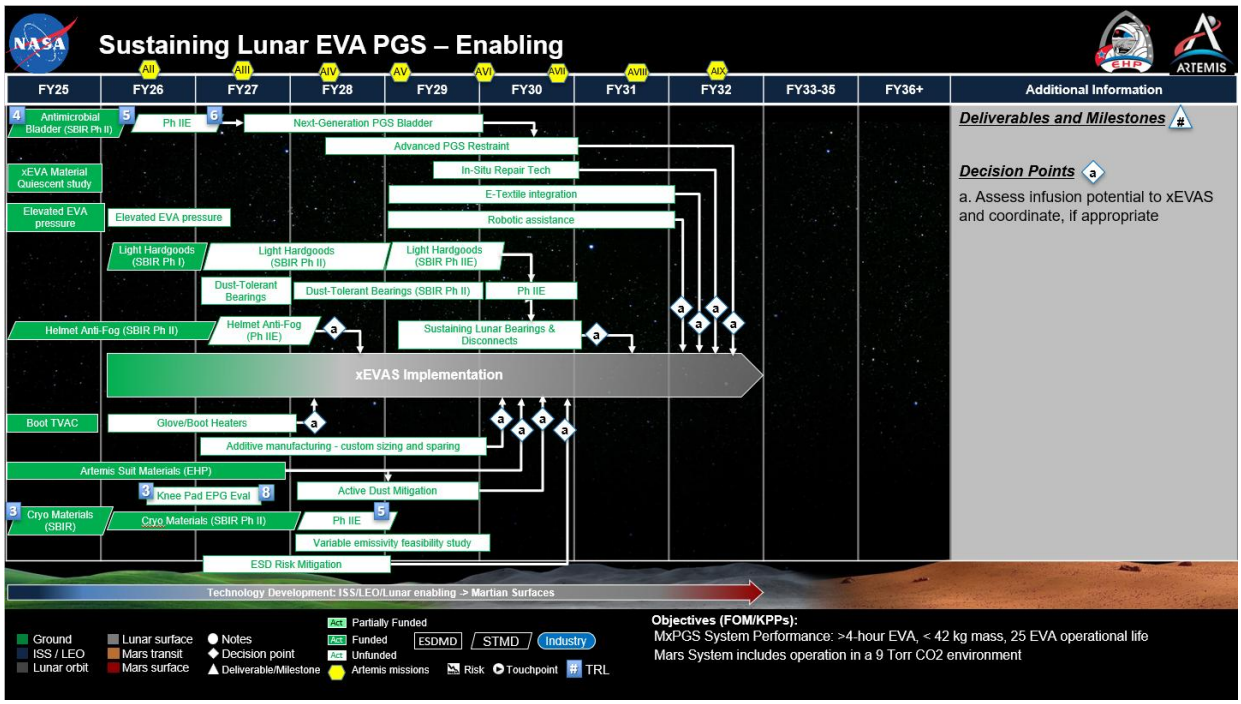


Figure 5. Sustaining Lunar EVA PGS – Enabling Roadmap.

c) *NASA-Funded "Lunar EVA PGS – Sustained Lunar Evolution Enabling" Investments*

- **CO_2 Washout Risk Assessment –** Three-phased approach to update the suited CO_2 washout methodology following NASA Engineering and Safety Center (NESC) findings/recommendations. Reassessment and redesign of the suited CO_2 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 and 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 coatings.
- **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.
- **Cryo Materials** – Non-fabric materials for the PGS, such as adhesives, room-temperature vulcanizing materials, boot soles, etc.
- **Light Hardgoods –** Lightweight structural and bearing material development

d) *Proposed Activities: "Lunar EVA PGS – Sustained Lunar Evolution Enabling"*

- **Knee Pad EPG Eval –** Knee pad EPG solution(s) DTO on Artemis III to evaluate candidate sustaining lunar fabrics
- **Glove / Boot Heaters** – Develop high efficiency, distributed heat glove and boot heater elements to close thermal gap in Lunar PSRs
- **Dust Tolerant Bearings** – Mature mobility element bearings that are tolerant or more resistant to dust intrusion and develop bearings that are easier to maintain in dusty environment
- **Next Generation PGS Bladder** – Mature advanced bladder with enhanced capability for SLE (anti-microbial, etc.)
- **Advanced PGS Restraint** – Develop / baseline SLE restraint materials
- **E-Textile Integration** – Investigate feasibility of incorporating E-Textiles to PGS suit materials for dust resistance, sensing, etc.
- **Active Offloading** – Investigate feasibility of incorporating active offloading to PGS to support EVA operations
- **In-Situ Repair Tech** – Investigate opportunities for in-field PGS repair, including self-healing and patch kits
- **Additive Manufacturing** – Inform bearings, disconnects, sizing features and bracketry as well as sparing strategy
- **SLE Bearings and Disconnects** – Develop bearings and disconnects for SLE that provide enhanced performance and/or reduced mass
- **Active Dust mitigation –** Investigate feasibility of incorporating active dust mitigation into the PGS EPG
- **ESD Risk Mitigation** – Investigate need and opportunities for mitigating risk of ESD
- **Variable emissivity feasibility study** – Investigate feasibility of variable emissivity coatings to provide Mars suit thermal control

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 (O_2) storage and pressure regulation for breathing and environmental habitability; CO_2 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 (International Space Station (ISS), lunar lander, rover) to recharge consumables, utilize a vehicle heat exchanger during intravehicular activity (IVA) operations, and access vacuum for CO_2 desorption while IVA.

Figure 1 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 focused roadmap

has been divided into four technical categories: 1) CO_2 Removal (Figure 6); 2) O_2 Supply and Ventilation (Figure 7); 3) Thermal Control (Figure 8); and 4) Avionics & Power (Figure 9).

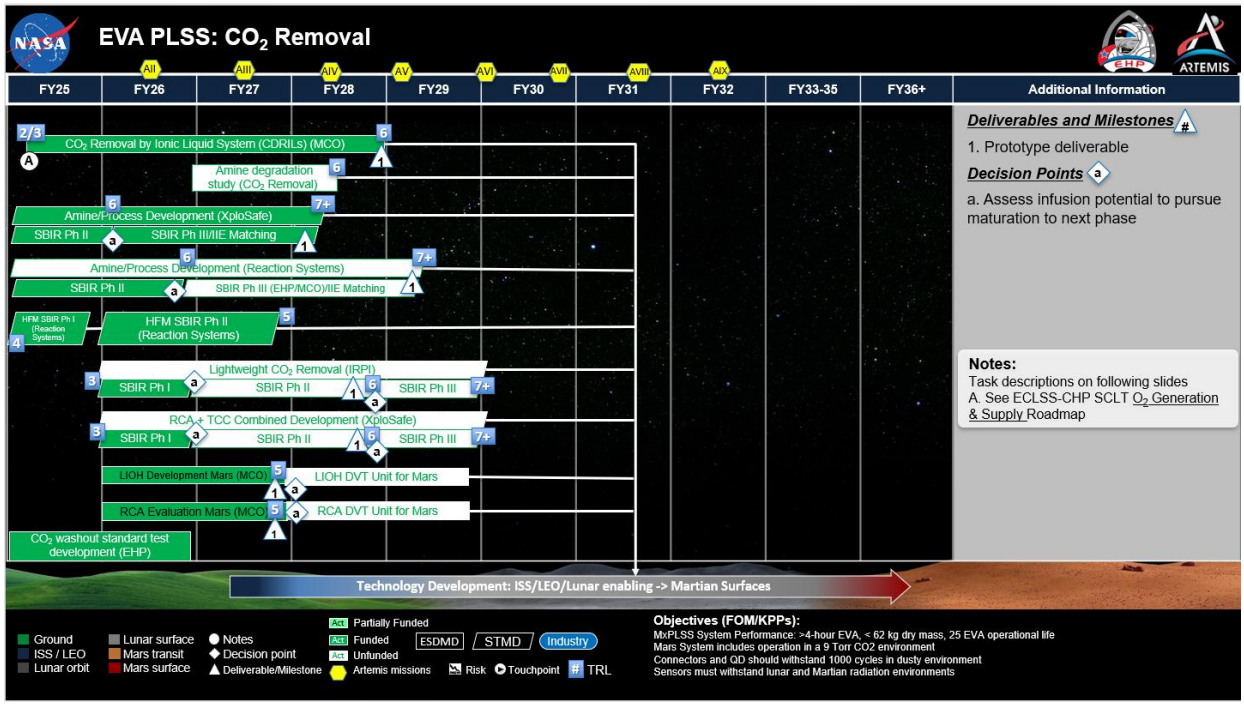


Figure 6. EVA PLSS – CO_2 Removal Roadmap.

1. CO_2 Removal
   a) NASA Funded "EVA PLSS: CO_2 Removal" Investments
   - **Amine/Process Development** – Nanoporous materials to provide CO_2 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)
   - **CO_2 Washout Standard Test Development** – In order to manage the CO_2 inspired by an astronaut, the spacesuit must scrub the CO_2 from the life support system, but the flow in the helmet must also carry the exhaled gas away from their oro-nasal region. Quantifying washout and inspired CO_2 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 CO_2 control, especially in this era of commercially provided suits.
   - **Hollow Fiber Membrane (HFM) –** Reaction Systems (Hollow Fiber Membrane) is looking into a method to remove CO_2 using a liquid sorbent
   - **CDRILS** – Carbon Dioxide Removal by Ionic Liquid System (CDRILS) non-venting, CO_2/H_2O sequestration. CDRILS will utilize a small hollow-fiber membrane scrubber with a circulating liquid absorbent that would absorb CO_2 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 CO_2/H_2O 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.
   - **RCA and Trace Contaminant Control (TCC) Combined Development** – If a CO_2 control sorbent could be developed that also captured trace contaminants, this could eliminate a component in the PLSS. Vacuum-Regenerable Sorbent System (XploSafe, LLC); TCC will also need testing.
   - **Lightweight CO_2 Removal –** IRPI is looking into a lightweight CO_2 removal solution
   - **Lithium hydroxide (LIOH) for Mars** – LIOH is a lightweight but non-regenerable solution for Mars that trades well for mass requirements on the suit and needs to be built and tested

- **RCA Evaluation for Mars –** The RCA swing bed and associated research will not work as is with the environment on Mars. Alternative methods to use this on Mars need to be investigated such as sweep gas.

b) Proposed Activities: "EVA PLSS: CO_2 Removal"

- **Amine Degradation Study –** Amines need to be evaluated for long term degradation for usage and storage

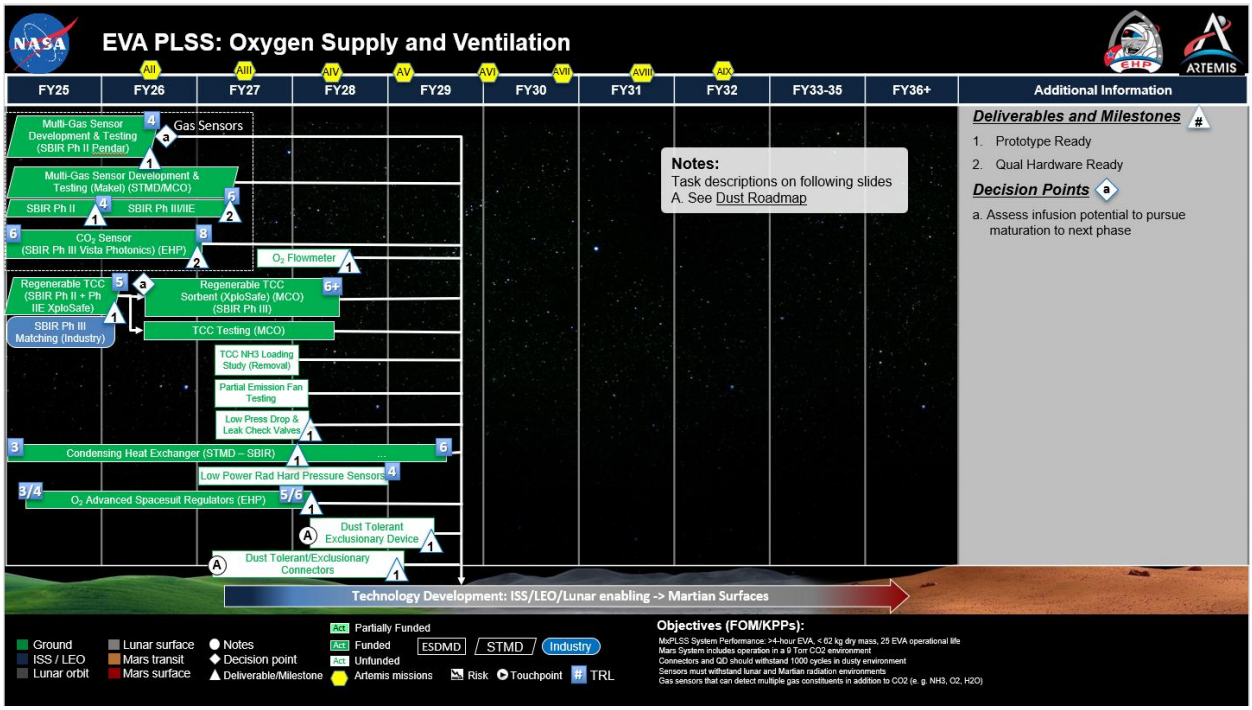


Figure 7. EVA PLSS – Oxygen Supply and Ventilation Roadmap.

2. O_2 Supply and Ventilation

a) NASA-Funded "EVA PLSS: Oxygen Supply and Ventilation" Investments

- **Multi-Gas Sensor Development and Testing** – The current ISS-EMU and xEMU have CO_2 sensors to monitor conditions in the suit. Low TRL efforts have previously evaluated multi-gas sensors that could also potentially measure humidity, oxygen, or ammonia. Four STMD projects were completed in 2023. Two SBIR multi-gas investments have continued into Phase II. (Pendar Technologies, LLC and Makel Engineering, Inc.) One SBIR multi-gas investment continued into Phase IIE and Phase III (Makel Engineering, Inc.). One CO_2 sensor development has continued into a SBIR Phase III flight development (Vista Photonics, Inc.).
- **Regenerable TCC** – Xplosafe is developing a regenerable TCC technology. This is needed to reduce consumable mass on orbit. These cartridges will be tested to verify functionality.
- **Condensing Heat Exchanger** – If using LiOH for Mars to save weight, humidity removal will need to be handled separately. A condensing heat exchanger is required.
- **O_2 Advanced Spacesuit Regulators** – Advanced, next generation O_2 regulator development is needed.

b) Proposed Activities: "EVA PLSS: Oxygen Supply and Ventilation"

- **O_2 Flowmeter** – Low Pressure Drop Oxygen Flow meter is needed for the PLSS.
- **TCC NH_3 Loading study –** Evaluate the performance of the TCC loaded with high amounts of NH_3 to simulate the contamination potential from the RCA.
- **Partial Emission Fan Testing** – This task would perform acceptance testing on fans purchased at the end of the xEMU project. This design offer the potential for low power requirements.
- **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 suit.

- **Low Power 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.
- **Dust Tolerant Exclusionary Device –** Dust tolerant exclusionary filters to protect the Exploration External Mobility Unit (xEMU) Rapid Cycle Amine Beds or SWME 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.
- **Dust Tolerant/Exclusionary Connectors –** 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.

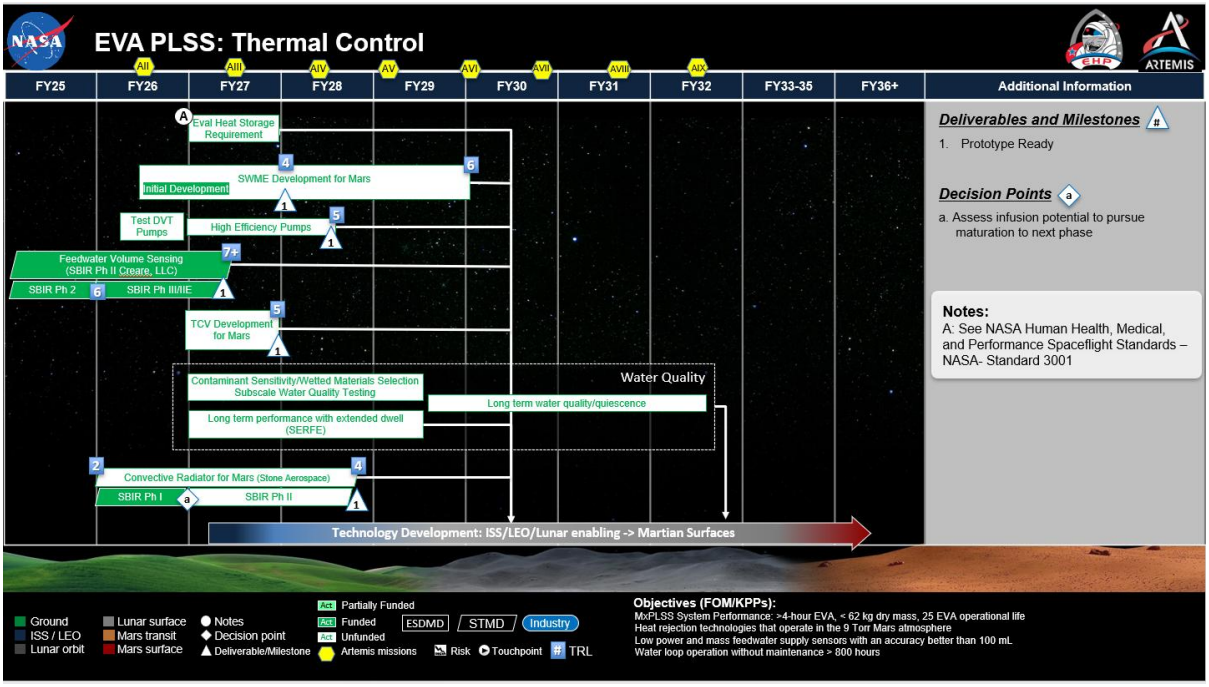


Figure 8. EVA PLSS – Thermal Control.

3. Thermal Control

a) NASA Funded "EVA PLSS: Thermal Control" Investments

- **SWME Development Mars** – The low-pressure CO_2 environment on Mars may degrade the performance of the SWME. The SWME needs to be assessed and developed for Mars. Initial development for Mars was initiated in FY26.
- **Feedwater Volume Sensing –** 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 remaining amount of water is critical to monitoring the duration of an EVA. Creare, LLC was funded for a SBIR Phase II for a Volume Sensor for Flexible Fluid Reservoirs in Microgravity which resulted in a flight demo on New Shepard, December 18, 2023, launch and analysis which proved successful. Currently, Creare is funded for Phase III and Phase IIE to further develop the technology.
- **Convective Radiator for Mars** – Stone Aerospace is exploring a convective heat exchanger for Mars utilizing the Mars atmosphere for cooling in an SBIR Phase I.

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.

- **SWME Development Mars** – The low-pressure CO_2 environment on Mars may degrade the performance of the SWME. The SWME needs to be assessed and developed for Mars.
- **Test DVT Pumps** – DVT pumps need to be tested to assess performance.
- **High Efficiency Pumps** – Continued development and evaluations of water pumps with lower power requirements is desired
- **TCV development for Mars –** A low TRL ball valve exists and needs to be developed further for Mars.
- **Contaminant Sensitivity/Wetted Materials Selection Subscale Water Quality Testing** – Water quality issues have plagued the ISS-EMU and other life support systems throughout NASAs history. xEMU-based technology development efforts for SWME and the 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. This includes sub-scale tests to assess materials or contaminants that might present performance issues to the current thermal control technologies.
- **Long term performance with extended dwell (SERFE)** – The SERFE unit should sit in quiescence where it is tested after long dormant periods (> 2 years) to evaluate quality.
- **Long term water quality / quiescence –** As vendor units are designed, finalized, and mission concepts are matured, these units should sit in quiescent evaluations for extended periods of time to evaluate water quality.
- **Convective Radiator for Mars** – Stone Aerospace exploring a convective heat exchanger for Mars utilizing the Mars atmosphere for cooling in an SBIR Phase I. If successful, Phase II would be desired.

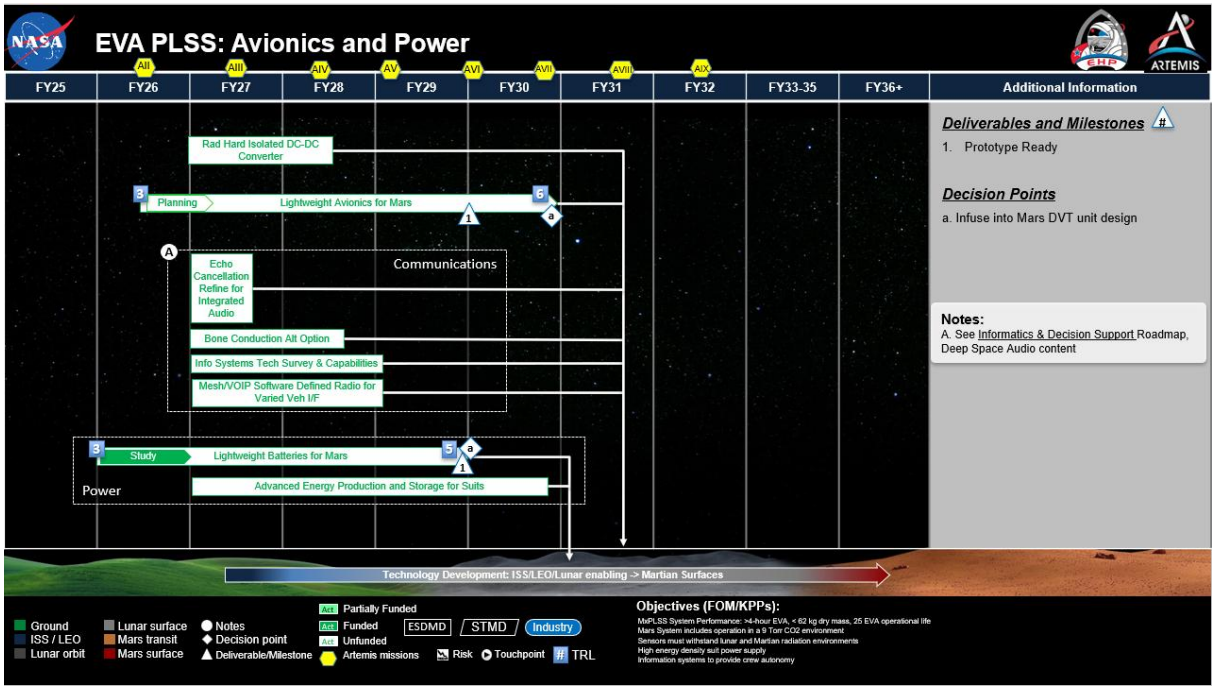


Figure 9. EVA PLSS – Avionics and Power.

4. Avionics and Power

a) NASA-Funded "EVA PLSS: Avionics and Power" Investments

- **Lightweight Batteries for Mars** – Commercial battery applications drive technology at a much faster rate than the space industry. A technical study is underway to assess emerging technologies for spacesuit applications which can provide improvements in energy density, which translates to longer EVAs and less massive batteries.

b) Proposed Activities: "EVA PLSS: Avionics and Power"

- **Radiation Hardened Isolated DC-DC Converter** – Development is needed for a self-calibrating, lightweight radiation hardened isolated DC-DC converter. Radiation hardened electronic components typically lag in performance as compared to consumer electronics.

- **Lightweight Avionics for Mars** – Avionics systems for Mars need to be developed with an emphasis on low power and lightweight to meet Mars mass requirements.
- **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 is needed. Options need to be explored such as 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 (VOIP) Software Defined Radio** – The ISS-EMU and xEMU still rely on a radio frequency-based radio infrastructure. 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.
- **Lightweight Batteries for Mars –** After the technical study has completed to assess emerging technologies for spacesuit applications, development is needed to improve 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.

E. Mars Exploration Extravehicular Mobility Unit (MxEMU) Integrated (Collaborative) Roadmap

While the development of the PGS and PLSS largely occurs independently, the ultimate goal is an integrated suit in which both subsystems work together to address the challenges posed by the Mars atmosphere. To support this objective, PGS and PLSS advanced development teams have created a collaborative roadmap that identifies key points of interdependency between PGS and PLSS. In Figure 10, the integrated suit architecture and cross discipline efforts are portrayed. In Figure 11, the integrated suit architecture and hardware design efforts are portrayed.

The notable milestones for the MxEMU include:

- FY 2028: Establishing a unified approach to thermal management
- FY 2030: Development of a PGS-PLSS mounting system after both subsystems are mature
- FY 2030: Delivering first-pass mass allocation breakdown in accordance with the SK-EC-EP collaboration
- FY 2034: Initiating development of an integrated unit

Given the aggressive timeline and the complexity of the MxEMU design, tasks will not proceed strictly sequentially. Several activities will iterate and infuse back into one another as designs mature. The roadmaps depicted in Figures 10 and 11 capture this intricate network of development efforts. Funding details have been omitted from these overview roadmaps, as each technical category encompasses multiple projects with varying funding sources. Those details are available within the dedicated PLSS and PGS sections of this paper.

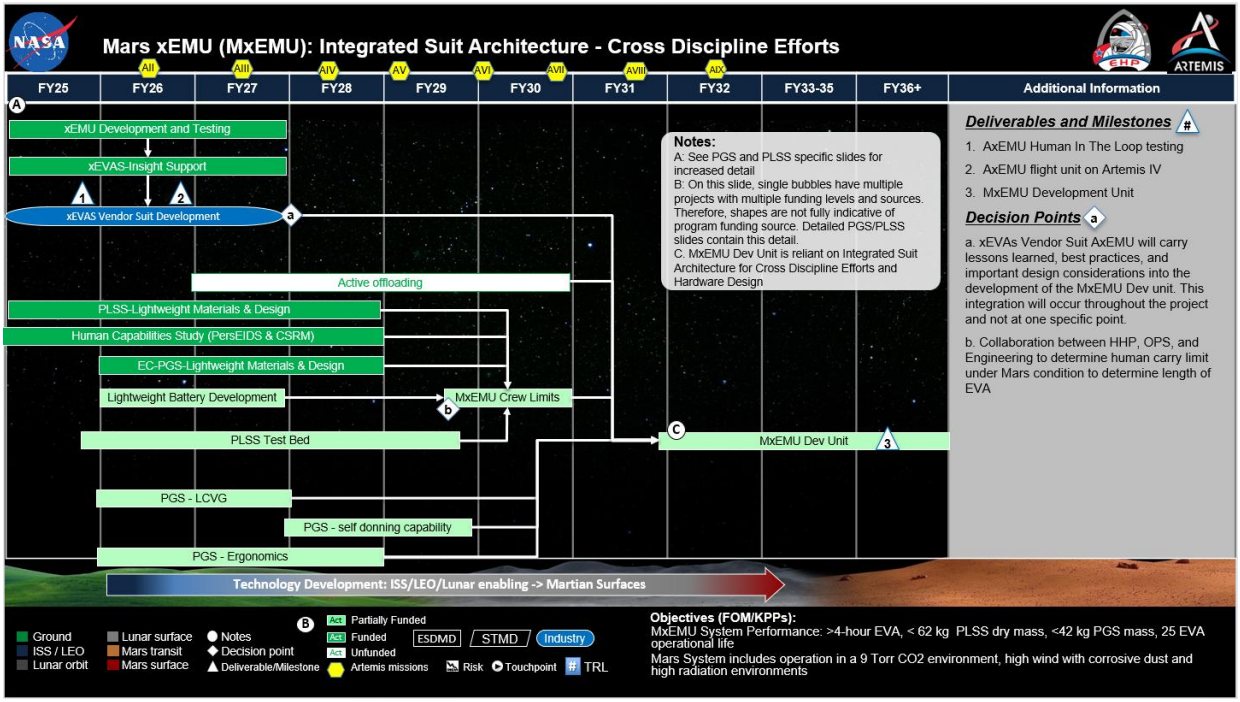


Figure 10. MxEMU – Integrated Suit Architecture-Cross Discipline Efforts.

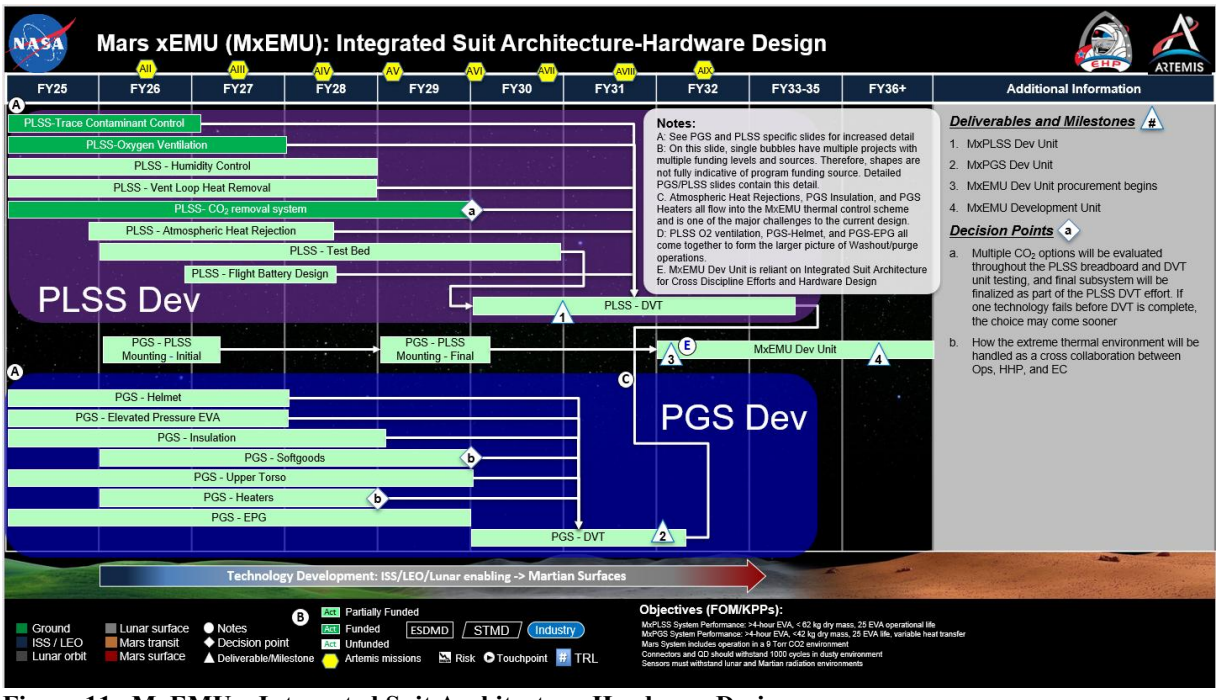


Figure 11. MxEMU – Integrated Suit Architecture-Hardware Design.

IV. Conclusion

The NASA EVA spacesuit technology roadmaps serve to organize spacesuit technology development required to explore the Mars environment. As they are implemented, EVA spacesuit technology roadmaps will provide enhancement to lunar mission capability as well. For each subsystem, the roadmaps provide a graphical view of the development path and, by implication, the method of infusing enabling technologies into a development unit and ultimately flight demonstration. The integrated roadmap shows a collaborative effort of disciplines and hardware design that is needed to progress to a MxEMU development unit. 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 technological 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 collaborations both internally and externally.

EVA spacesuits symbolize human space exploration. EVA spacesuit 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 spacesuit 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 EVA spacesuit technology 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.

Acknowledgments

The authors would like to give credit to the engineers that work hard to develop, design, test, and evaluate technology. They embody the Crew and Thermal Systems Division's motto, "Pioneering Technology to Live and Work in Space."

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