NASA Advanced Space Suit Pressure Garment System Status and Development Priorities 2024

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This paper discusses the current focus of NASA's Advanced Space Suit Pressure Garment Technology Development team's efforts, the status of that work, and a summary of longer term technology development priorities and activities. The Exploration Extra-vehicular Activity Mobility Unit (xEMU) has been the team's primary effort over the past several years. This paper documents the various tests executed with the xPGS to evaluate its performance, durability, and acceptability for microgravity and Lunar missions. An overview of ongoing and planned xEMU testing and training is provided. The PGS team's efforts in supporting the Exploration Extravehicular Activity Services (xEVAS) vendors is discussed. In addition, technology development efforts in coordination with the EVA and Human Surface Mobility Program (EHP), the NASA Engineering Safety Council (NESC) and the Small Business Innovation Research (SBIR) Program will be discussed in the context of supporting sustaining EVA operations on the Lunar surface over the coming decade. Finally, a brief review of longer-term pressure garment challenges and technology gaps will be presented to provide an understanding of the advanced pressure garment team's technology investment priorities and needs.

Nomenclature

ARGOS	=	*Active Response Gravity Offload System*
ABF	=	*Anthropometry and Biomechanics Laboratory*
AST	=	*Advanced Suit Team*
CO_2	=	*carbon dioxide*
DVT	=	*Design Verification Testing*
EHP	=	*EVA and Human Surface Mobility Program*
EMU	=	*Extra-Vehicular Mobility Unit*
EPG	=	*Environmental Protection Garment*
ESP	=	*Elevated Suit Pressure*
EVA	=	*Extra-Vehicular Activity*
GFE	=	*Government-Furnished Equipment*
HITL	=	*Human-in-the-loop*
HLS	=	*Human Landing System*
HUT	=	*Hard Upper Torso*
ISS	=	*International Space Station*

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ITT = *Integrated Test Team*
LTV = *Lunar Terrain Vehicle*
MWC = *Multiple Water Connector*
NASA = *National Aeronautics and Space Administration*
NBL = *Neutral Buoyancy Laboratory*
NESC = *NASA Engineering Safety Council*
PGS = *Pressure Garment Subsystem*
PLSS = *Portable Life Support System*
POGO = *Partial Gravity Simulator*
PSR = *Permanently Shadowed Region*
SBIR = *Small Business Innovative Research*
SxEMU = *Short Exploration Extra-Vehicular Mobility Unit*
STTR = *Small Business Technology Transfer*
TVAC = *Thermal Vacuum Chamber*
xEMU = *Exploration Extra-Vehicular Mobility Unit*
xEVAS = *Exploration Extra-Vehicular Activity Services (contract)*
xPGS = *Exploration Pressure Garment Sub-system*

I. Introduction

ARTEMIS III, the NASA mission to land humans on the surface of the Moon for the first time in more than 50 years, is currently scheduled for 2026 with Artemis IV and V shortly thereafter. In addition, the dwindling fleet of EMU hardware to support International Space Station (ISS) EVAs has continued to cause logistical challenges. New suits are under development to support both of these missions. The Advanced Space Suit Pressure Garment Technology Development team ("Advanced Suit Team") at NASA's Johnson Space Center continues to work cultivating the development of spacesuit assemblies and technologies to enable NASA to meet its human exploration goals. The Exploration Extra-Vehicular Mobility Unit, or xEMU, had been the primary focus of the Advanced Suit Team for the past several years. Assembly of multiple full xEMU pressure garment (xPGS) assemblies and subsystem Design Verification Testing (DVT) were completed in the summer of 2022. Multiple publications have recently documented the xPGS assembly[1] and components[2,3,4,5,6,7,8,9,10] design, as well as results from DVT as it relates to mobility and cycle life performance[12,13]. The xPGS suit assembly is being utilized in the EVA and Human Surface Mobility Program (EHP) to develop test infrastructure and interfaces, conduct integration evaluations, and develop training plans for the Artemis missions. Significant test series include Neutral Buoyancy Laboratory (NBL) evaluations, ARGOS return to service, thermal vacuum chamber testing, and elevated pressure testing. Lessons learned from those tests and about the xPGS suit's performance will be briefly discussed.

Meanwhile, the team has transitioned to supporting the eXploration Extra-Vehicular Activity Services (xEVAS) contract and the two contracting partners, Collins Aerospace and Axiom Space. Lastly, we have focused technology development efforts on sustaining Lunar operations and the specific challenges of those missions.

This paper highlights all these ongoing technical efforts in support of both Artemis and International Space Station (ISS) programs, as well as future NASA missions to human exploration destinations.

II. Commercial Services Suit Development

The Apollo and EMU suits were completed on large government cost-plus contracts by teams of private companies responsible for meeting the technical requirements, deliverables, and schedule. The engineering, fabrication, assembly, testing, certification, and delivery of the suits to NASA were completed by these companies. In contrast, the xEMU project was originally devised as a government-furnished equipment (GFE) effort. NASA-led teams at JSC conducted the assembly-level engineering and design, sometimes in tandem with contractors delivering components or individual parts. The NASA-led teams were also responsible for assembly, testing, and certification. Therefore, the xEMU project was a significant departure from every previous EVA suit development.

However, as the Artemis program matured, successes in the Commercial Cargo and Crew programs were catalysts for a change to Artemis suit procurement strategy. Under the new approach, called xEVAS (eXploration Extra-Vehicular Activity Services), NASA pays a fixed price for a vendor to provide an EVA service to support NASA missions in a similar way that Commercial Crew vendors provide a launch and ISS ferry service. The vendors are responsible for not only the suit design and fabrication but maintain ownership of the hardware itself. The vendors will also be required to provide suit maintenance, logistics, and sustaining engineering. Under the xEVAS contract, the complete xEMU reference design, NASA testing facilities, and NASA xEMU personnel have been made available for use by the vendor to leverage how they deem appropriate to meet technical and deliverable requirements.

NASA has awarded the xEVAS contract to two vendors, Axiom Space and Collins Aerospace. The work under the contract is further authorized by the award of task orders. As of January 2024, Axiom Space has been awarded a task order to deliver the EVA system for the Artemis III mission, and Collins Aerospace has been awarded a task order to develop an EVA system for the International Space Station. In addition, both vendors have received a supplemental task order to evaluate the capability of their suit system to support both Lunar and ISS EVA destinations.

The Advanced Suit Team is currently supporting all task orders through clearly defined support mechanisms identified in the xEVAS contract. Under the *Insight* support role, NASA personnel ensure that vendor development plans, designs and deliverables are consistent with contract requirements and will ensure NASA mission success. To effectively review deliverables and have necessary insight into the vendor process, the Insight team and vendors are continuously in communication to provide feedback on process and deliverables to ensure quality products at the key milestones. Due to providing Insight to both vendors and the high number of deliverables requiring review at one time, the Advanced Suit Team currently has approximately 5-6 team members fulfilling the xEVAS Insight role. The Insight role also include identification and communication of program risks to the program office. In many cases it may be necessary for NASA to develop mitigation plans to technical or schedule-based risks if they fall outside of the current task order scopes that have been awarded.

Under the *Collaboration* support role, NASA personnel augment the xEVAS vendor teams to aid in development and hardware certification, as well as to gain detailed understanding of the hardware designs to facilitate additional support and identify NASA risk mitigation activities for future missions.

Due to the competitive procurement environment, NASA and NASA supporting contractors have implemented strict firewalls between team members as necessary. To ensure the success of the xEVAS procurement strategy, NASA recognizes the vital importance of protecting vendor information and intellectual property.

III. Testing and Integration

After completion of the xPGS subsystem DVT Testing, the xPGS test team transitioned to supporting the EHP office by conducting a series of other tests as prioritized by the program. The xPGS test team was renamed the Integrated Test Team (ITT), a sub-team of the overall Advanced Suit team. The test team utilizes the xPGS government reference design hardware to support the program's objectives. During the 2023 fiscal year the ITT conducted 128 separate suited human in the loop (HITL) test events, with 53 different test subjects, and in 10 different facilities.

Some of the test series that are focused on suit performance and engineering objectives are summarized below. In addition to these tests, the ITT supported Rockyard tool and ops con evaluations, crew planetary suit familiarization tests, Lunar Terrain Vehicle (LTV) interface tests, HLS elevator interface tests, and NBL partial gravity facility development tests. The Integrated Test Team also worked with xEVAS vendors as members of the test teams to aide in test planning and approval of test readiness reviews for various test events.

A. Thermal Vacuum Suit Testing

The subsystem DVT testing concluded in 2022, but system-level testing continued with the first suit system thermal vacuum testing conducted since Apollo. The test was initially planned to be limited to a short xEMU test with the objective of evaluating the functionality of the portable life support system in the thermal vacuum chamber, but the test was moved to Chamber B for cost and schedule reasons, which enabled the team to also add a full xPGS suit test article.

The goal of the SxEMU (assembly composed of the PLSS, Upper Torso, helmet, and EVVA) test was to demonstrate the ability of the xEMU to meet life support functionality, including suit pressure, temperatures, flow rates, and CO2, humidity and trace contaminant removal. It provided full characterization of the xEMU thermal performance and contingency functions. The second test article was a full xPGS with simulated thermal interfaces for the crew and xPLSS. This test provided additional data on xPGS thermal performance, including gloves and boots.

Testing was successfully completed in October of 2023 with the data analysis on-going. Overall test results will be documented in ICES-2024-75, with detailed analysis in ICES-2024-76, 130, 213, 215, 216, 217 and 219.

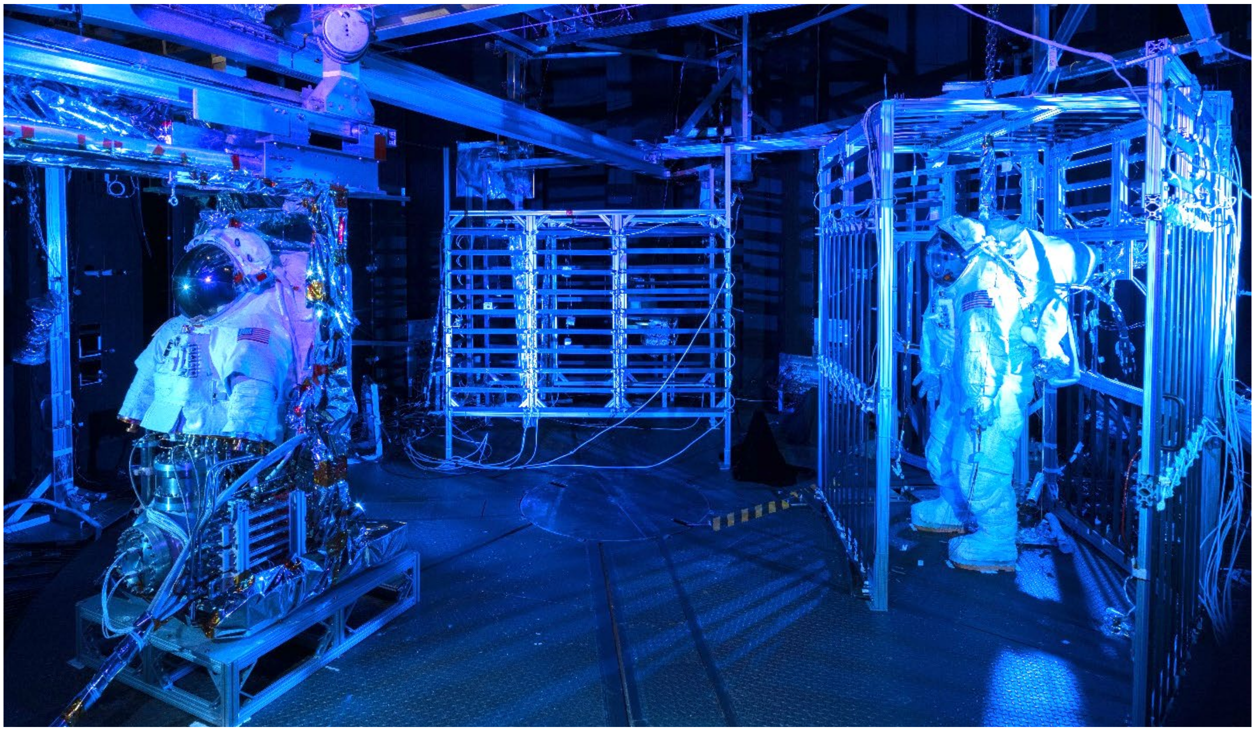

Figure 1: xEMU Thermal Vacuum Chamber Test with the SxEMU on the left and the full xPGS on the right

B. Shoulder Strap Testing

The Advanced Suit Team is continuously trying to improve their ground-based test capabilities and processes. A potential confounding factor that many ground-based tests face is that the subject has to support the weight of the PGS and the associated test support equipment. This weight and the effect on 1-g fit can affect test objectives if not effectively accounted for. The AST wanted to better quantify the self-supporting nature of the xPGS suit and use this data to more consistently fit test subjects. Towards that end, the team partnered with the Anthropometric and Biomechanics Facility (ABF) to develop a load sensing shoulder harness assembly. By measuring the load in the shoulder harness, the team has better insight into the subject's fit and how that fit can affect 1-g test objectives. The team plans to incorporate this capability into nominal fitcheck operations. Additional details of the design and test results is documented in ICES-2024-158.

C. Simulation Quality

Several test environments exist to simulate the lunar gravity environment. These include the Active Response Gravity Offload System (ARGOS), parabolic flights, and the neutral buoyancy lab (NBL). Each of these test facilities have strengths and weaknesses that make them more or less appropriate, depending on the objectives of a test or training event.

ARGOS has been used extensively over the past several years to conduct DVT testing for the xPGS suit. ARGOS has been a crucial test bed to evaluate gross suit mobility and tools in a relatively low overhead facility. Systematic mobility or cycle testing of the xPGS hardware wouldn't have been possible without the use of the ARGOS system. However, ARGOS was shutdown for more than 8 months following an incident in May in which the lift system inadvertently drove the suit to the end of the test area. While no one was injured in this event, an investigation was conducted and changes to the operating procedures were made to improve the system safety. ARGOS has a relatively small test area, can only offload one test subject, relies on a gimbal system, that has limited roll pitch and yaw simulation quality, and cannot offload appendages or tools that are handled. A new system called AX3S is intended to address several of these shortcomings by providing a larger test area and the ability to offload 3 test subjects at a time, but that system is more than a year away from being operational.

Parabolic flight has been used extensively to simulate partial gravity environments since Apollo. Parabolic flight provides the most realistic gravity environment as it is the only one in which the person's body is also at a reduced gravity, in addition to the suit, thus creating a realistic human suit interaction and overall center of gravity. However, parabolic flights are limited based on ~15 second partial gravity parabola and a limited test area, making it most useful to validate other test facilities or aide interpreting the results from other test facilities.

Use of the neutral buoyancy lab environment to simulate partial gravity effects is a relatively new concept. The NBL is used extensively to train astronauts for micro-gravity. In order to simulate partial gravity, an additional 60-100 lbs are added to the suit in a distributed manner to provide approximately correct ground reaction force, appendage masses, and center of gravity. An extensive amount of testing was conducted to improve and understand the simulation quality of the NBL facility to understand how it can be used for future evaluations and training. However, a lack of cohesive simulation quality assessment and validation testing have left the team with significant concerns about how results from NBL testing can be used. Details of the testing and a more extensive discussion of the simulation quality is documented in ICES-2024-110.

D. Elevated Suit Pressure (ESP) Testing

The xEVAS requirements document assumes an exploration vehicle atmosphere of 10.2 psia and 27% O2 or 8.2 psia and 34% oxygen. Vehicle atmospheres in the 30% range or higher has created a materials identification hurdle and presents schedule risk to the program. NASA has kicked of a test campaign to evaluate the risk associated with having a higher EVA suit pressure which could minimize pre-breathe time and provide some relief on the vehicle oxygen concentration level. The test series includes 4 different test series: 1) Glove box testing to evaluate the relative fatigue risk of operating at a pressure of 6.2 psid, in comparison to the current nominal pressure of 4.3 psid. 2) NBL partial gravity testing, that is intended to evaluate cumulative fatigue from conducting an end-to-end EVA with two crewmembers and a realistic test cadence at a pressure of 6.2 psid. 3) ARGOS testing will evaluate gross mobility tasks to evaluate impacts to overall mobility and at an elevated pressure of 6.2 psid. And 4) ARGOS based cycle testing will be conducted to evaluate the relative reduction in cycle life with a suit that is operated at 6.2 psid. At the time of the writing of this paper, glovebox testing is complete and data from those tests is currently being evaluated. The first three NBL test events have taken place, but problems with communication systems, weigh-out and test subject have resulted in little data collected for two of these runs. The program has approved additional testing in the NBL, which will take place in May. ARGOS testing has concluded, and ESP tests are expected to begin in the Spring.

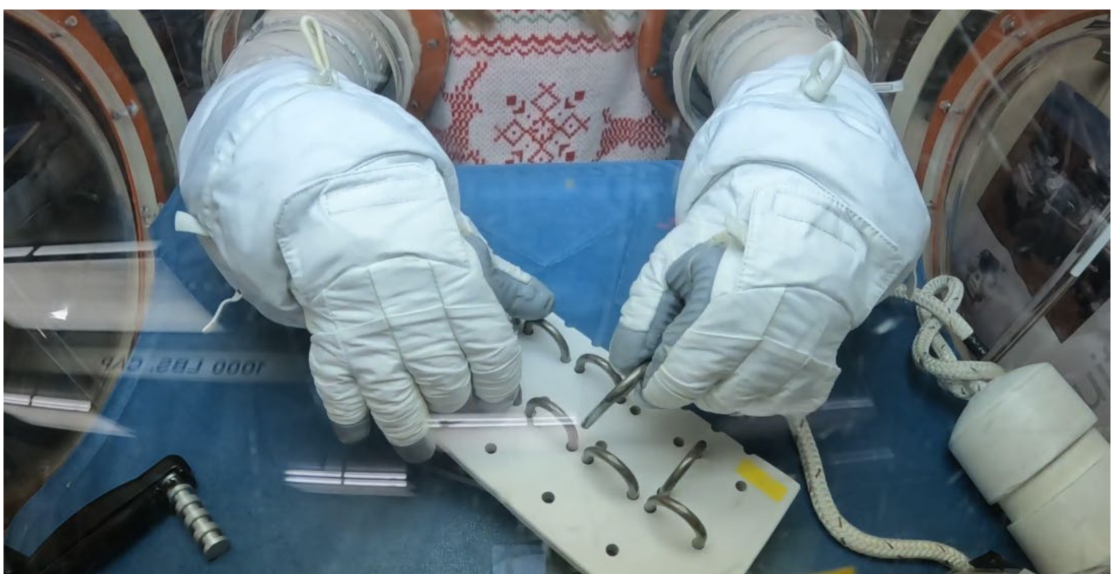

Figure 2: Test subject conducting pegboard operations in the glovebox elevated suit pressure test

E. Lessons learned / Anomalies on xPGS Suit

The xPGS continues to be an extremely valuable testbed for the EHP program. DVT PGS testing concluded with mobility and cycle testing of the small HUT. Most of the tests in which the xPGS suit is being utilized aren't designed to learn more about the suit and its performance, but to utilize the suit as a test bed for operational and integration objectives. However, the team still works to learn as much about the suit design's strengths and weaknesses and look for applications to future suit development. The large HUT wasn't initially part of the xEMU project's scope and wasn't ready in time for DVT. However, since DVT concluded the large HUT has been used for crew familiarization and simulation quality evaluations in the NBL and POGO facilities. These large HUT evaluations have highlighted some shortcomings in the fleet sizing analysis and design work. Primarily, the fleet sizing analysis was conducted on the large HUT structure and brief structure, with little testing or analysis done on the rolling convolute waist between. The rolling convolute joint provides significant mobility in a short height by allowing the brief to nest within the outer ring. This nesting and the volume required for the PTLC and ATLC connectors has created some discomfort and a very tight fit for larger test subjects in the abdomen region. This has not been a problem in the EMU waist joint as it has significant volume for crew anthropometry and the MWC. To address this issue sufficiently for crew across the full anthropometry range, possible solutions are altering the waist flexion extension joint geometry, altering the architecture for taller/larger test subjects, or re-routing of the connectors.

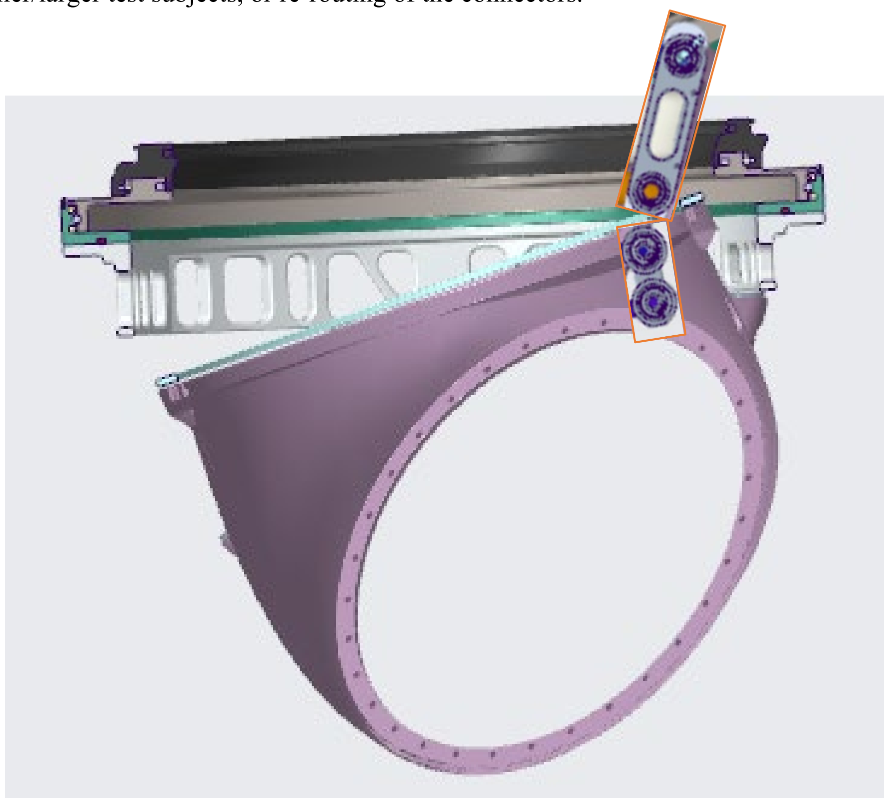

Figure 3: Cross-section of WBH showing brief position when fully flexed including PTLC and ATLC

F. Analog Suit Testing

In order to adequately train astronauts for lunar operations it is necessary to train in a variety of environments. Training on the suit's mobility will take place in facilities that can best simulate the lunar environment. Shirt sleeve training will take place to teach the crew geology, use of tools, and operations concepts. To fill the gaps between shirt sleeve and pressurized suit testing, analog suits will be used to add some realistic mobility restrictions and operational restrictions, that are absent when doing shirtsleeve tasks. To that end the Advanced suit team has been supporting Joint EVA Tests where training flows and protocols are being developed for the Artemis crew. The designs and use of NASA's mock-up suits has been covered previously [16]. Since the initial development of these mock-up suits the team has undergone significant effort to reduce the mass and increase the comfort of these mock-ups. The team was able to reduce the mass by more than 25 pounds, depending on the test electronics and tool operations, while also significantly improving subjective feedback from crew on the waistbelt comfort. The mock-up suits are a useful tool to meet specific test and training objectives, but are not representative of flight like mobility, comfort, metabolic expenditure, or fatigue. The team continues to work diligently to improve the use and usefulness of NASA's mock-ups.

IV. Risk Identification and Mitigation

Implicit to the commercial services procurement strategy is the assumption that private companies are best positioned to provide human spaceflight architecture that also serves an emerging commercial market and a corresponding profit incentive outside of NASA. In contrast, NASA is best positioned to conduct longer-term research and development which does not currently have or may never have a profit incentive.

Therefore, the Advanced Suit Team at JSC continues to look toward the future of suit development to be ready for what comes next. Current xEVAS task orders will produce a replacement of the EMU suit to support ISS missions through 2030 and initial Lunar EVA capability. As the Moon to Mars Program and Artemis missions progress, NASA will continue to identify and close strategic technology gaps through research and development activities to buy down risks and enable new capabilities in support of the Moon to Mars Objectives. The Advanced Suit Team at JSC views these technology development needs and opportunities mapped to identified risks to NASA missions.

In this context, below are the significant technology development efforts for the team as of FY24.

A. NASA Engineering Safety Council (NESC) glove risk mitigation

While the xEVAS vendor for Artemis III is responsible to deliver Lunar gloves and to meet associated technical requirements, additional task orders for later Artemis missions have yet to be awarded. Therefore, longer-term durability requirements that would be associated with a sustaining presence at the South pole of the Moon may not be prioritized. The NESC coordinated and funded a project including advanced suit team personnel as well as representatives from other organizations across and outside of NASA to assist in mitigating the risk of not having acceptable gloves to support sustaining Lunar operations under the Artemis program long term.

This project ran from in June 2022 to February 2024 and included extensive glove textile testing, dust testing, and thermal testing to address the specific challenge of Lunar PSRs. As part of the project, pressurized gloves were exposed to extreme cryogenic temperatures below 50K. This project has provided not only extensive knowledge around glove materials and design that will help address the risk going forward, but also standards which can be used to evaluate glove performance as well. For extensive documentation on this project and its various sub-tasks, the reader will refer to the following publications:

- ICES-2024-050, *Validation Testing and Statistical Analysis of the Rotary Tumbler Fabric Abrasion Method*
- ICES-2024-052, *Establishing a Standardized Test Method for Evaluating the Cut Resistance of Space Suit Glove Fabrics at Cryogenic Temperatures*
- *Establishing a Standardized Test Method for Evaluating Space Suit Gloves Thermal Performance at Lunar South Pole Temperatures*, to be published at next year's ICES

B. Artemis Suit Materials textile development

The Technology Development and Partnerships office (JSC Mailcode: DT) of the EVA and Human Mobility Program (EHP) has also recognized the risk associated with sustaining EVA operations on the Lunar surface as it pertains specifically to suit and glove environmental protection garments (EPG). Therefore, DT has funded a multi-year project, *Artemis Suit Materials*, which aims to leverage prior and new material testing, including cryogenic and dust exposure testing, with the goal of developing a bespoke outer EPG material that will meet sustaining Lunar EVA missions. This project, executed by the Advanced Suit Team, started in June 2023 and is expected to run through FY26. It will include custom development of a bespoke outer EPG fabric and evaluation of that fabric in environmental coupon testing and a human thermal vacuum glovebox test. Future papers will provide more detailed status and results.

C. SBIR / STTR

Under the Small Business Innovative Research (SBIR) and Small Business Technology Transfer (STTR) programs at NASA, the Advanced Suit Team is strategically pursuing technology development efforts that may enable risk mitigation and future NASA missions. As of this writing, these efforts include the following:

- EPG textile and material development
- Persistently antimicrobial suit bladder materials
- Advanced water connectors
- Permanent helmet anti-fog coatings and technologies

As the agency continues to support sustaining operations at the ISS as well as the Artemis program, the advanced suit team will continue to cultivate an SBIR and STTR portfolio that addresses technology gaps posing programmatic risk to these missions, as identified on the EVA Technology Development Roadmap presented in ICES-2024-022.

D. LTV AIB

LTV vendors will be responsible for producing the vehicle and suit vendors are providing the suits that ride on these vehicles. A risk was identified on the ability of the integrated suit-LTV system to protect crew from injury in the event of a crash. To mitigate that risk our team was involved in an Applied Injury Biomechanics (AIB) study to evaluate injury potential. The study did identify requirement gaps and potential injury for suited crewmembers. Additional work is required in order to validate the modeling work, investigate head position with xEVAS suits and mitigate the risks. Summary of the LTV study and resultant risks are summarized in ICES-2024-205.

E. PGS Technology Development Roadmap

In collaboration with the Technology Development and Partnerships Office of EHP, the Advanced Suit Team has baselined a new technology development roadmap for Sustaining Lunar and Mars EVA pressure garment capability. This roadmap conveys the technology development tasks to address current EVA gaps and risks for these missions, but also the underlying strategy and touchpoints with other EVA systems that best position NASA to close these gaps and risks in sufficient time to support associated missions.

More information about this roadmap, its implementation strategy, and availability to industry and academia is available in ICES-2024-022, *NASA Extravehicular Activity Technology Development & Maturation for Exploration.*

V. Conclusion

The Advanced Suit Team at JSC continues to adapt to the changing landscape of exploration missions and commercial services. The Advanced Suit Team continues to position itself strategically to best leverage its extensive knowledge and expertise to close EVA gaps, technical risks, and facilitate the next generations of advanced pressure garment hardware. We are aggressively pursuing new opportunities to ensure that technologies continue to advance to meet the needs of future Artemis and Mars missions.

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