54th International Conference on Environmental Systems
13-17 July 2025, Prague, Czech Republic ICES-2025-385

# NASA Advanced Space Suit Pressure Garment System Status and Development Priorities 2025

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**This paper discusses the current focus of NASA's Advanced Space Suit Pressure Garment team's efforts, the status of that work, and a summary of longer-term technology development priorities and activities. This paper documents the various tests executed with the Exploration Extra-vehicular Mobility Unit (xEMU) over the past year. 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 and the current flight EMU program is discussed. In addition, technology development efforts in coordination with the EVA and Human Surface Mobility Program (EHP) 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, as well as Mars missions for the future. 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 |
| BSC | = | Body Seal Closure |
| CDR | = | Critical Design Review |
| $CO_2$ | = | carbon dioxide |
| DVT | = | Design Verification Testing |
| EHP | = | EVA and Human Surface Mobility Program |
| EMITS | = | EMU Moisture Injection Test System |
| EMU | = | Extra-Vehicular Mobility Unit |
| EPG | = | Environmental Protection Garment |
| ESP | = | Elevated Suit Pressure |
| EVA | = | Extra-Vehicular Activity |
| GFE | = | Government-Furnished Equipment |

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|---|---|---|
| HITL | = | Human-in-the-loop |
| HLS | = | Human Landing System |
| HUT | = | Hard Upper Torso |
| JSC | = | Johnson Space Center |
| ISS | = | International Space Station |
| ITT | = | Integrated Test Team |
| LEDM | = | Lunar Electro-Static Discharge (ESD) and Dust Mitigation |
| LTV | = | Lunar Terrain Vehicle |
| MPH | = | Multi-Purpose Habitat |
| 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 |
| RIV | = | Requirements Integration Verification |
| SBIR | = | Small Business Innovative Research |
| SxEMU | = | Short Exploration Extra-Vehicular Mobility Unit |
| STTR | = | Small Business Technology Transfer |
| TCA | = | Task Capability Assessment |
| 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

The Advanced Space Suit Pressure Garment Technology Development team ("Advanced Suit Team," patch at right in Figure 1) at NASA's Johnson Space Center (JSC) continues to support NASA's agency goals to maintain American leadership in exploration and return to the Moon. The primary flux of this effort is through the Artemis Moon to Mars mission objectives. As of January 2025, the first manned Moon landing mission of Artemis, Artemis III, is targeting mid-2027. Subsequent Artemis missions will include additions to agency supported Lunar architectural assets including Gateway, Lunar habitats, Lunar Terrain Vehicles (unpressurized rovers), Pressurized Rovers, and proceeding then with subsequent Mars related missions. Currently the Advanced Suit Team is supporting efforts on several fronts including support of Commercial Service Suit development, Integrated Testing, Risk Identification and Mitigation related to suits and EVA systems, and Technology Research and Development. The Government reference model suit, the Exploration Extra-Vehicular Mobility Unit, or xEMU, and its pressure garment (xPGS) assemblies continue to be a prime tool supporting many Advanced Suit Team tasks. The team also incorporates the use of some historical suits (like the Mark III and Z-2 architecture) as well as Analog (mockup) suits as appropriate. The Exploration Pressure Garment Sub-system (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. In addition to supporting the Artemis efforts, the team also continues to support commercial efforts to replace the aging fleet of International Space Station (ISS) Extra-Vehicular Mobility Unit (EMU) suits, as well as technology development activities that may provide advancements in and beyond Artemis missions. Significant test series continue to include using NASA facility assets like the Neutral Buoyancy Laboratory (NBL) evaluations, ARGOS, and thermal vacuum chambers to name a few.

**Figure 1. Advanced Suit Team patch.**

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 originally awarded the xEVAS contract to two vendors, Axiom Space and Collins Aerospace. The work under the contract was further authorized by the award of task orders for development of Lunar and ISS suits. In June of 2024 Collin's Aerospace informed NASA that it would end work on spacesuit development and that no further work would be performed on the task orders. This has left the only currently active commercial space suit development activities under the xEVAS contract to a single vendor for NASA for Artemis III and the ISS suit replacement demonstration, to Axiom Space. Multiple vendors developing EVA services solutions greatly reduced NASAs risk posture for mission success. As a result of the reduction to a single vendor, NASA program management have been evaluating options to reduce the overall mission risk with the single vendor.

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. The Insight role also include identification and communication of program risks to the vendors and 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.

The Advanced Suit Team's efforts to help address technology gaps and risks have been identified as a priority for the team by the NASA Engineering directorate, EHP, and the agency due to the competitive nature of returning to the Moon. This is specifically necessary with only one commercial vendor willing to remain on the contract task orders.

Due to the procurement's commercial approach, NASA and NASA-supporting contractors have implemented strict firewalls as necessary. This is to ensure the success of the xEVAS procurement strategy, and the fact that NASA recognizes the vital importance of protecting vendor information and intellectual property.

## III. Testing and Integration

Starting in 2023 the Advanced Suit Team's testing team was renamed the Integrated Test Team (ITT) and its scope was expanded from a focus on strictly supporting development testing of the xEMU/xPGS, to focus more on providing support services to EHP prioritized Artemis mission related testing. In addition, it supports Government Task Orders, Space Suit Human in the loop testing by vendors at NASA facilities, and Engineering and Advance Suit Team internal testing.

During the 2024 fiscal year the ITT conducted 182 separate suited Human In The Loop (HITL) test events, with 7 different styles of suits, and in 11 different facilities. The primary suit for testing by the ITT continues to be the xEMU/xPGS which comprised about 40 percent of the events.

Tests supported ranged from field tests, Human Landing System (HLS) integration tests, Lunar Terrain Vehicle (LTV) evaluations, Lunar Multi-Purpose Habitat testing (MPH), Requirements Integration Verification (RIV) data runs, Lighting Lab evaluations, tool and ops con evaluations, crew planetary suit familiarization tests, to name a few.

The effort necessary to support the high volume of unique tests that were requested is higher than traditional EMU ISS training events due to each test requiring a large amount of one-off documentation and coordination between groups and facilities. Many of the groups involved in testing do not have previous experience with HITL testing.

The Integrated Test Team also worked with xEVAS vendors as members of the test teams for both vendor-led tests that include NASA personnel as test subjects, as well as NASA-led tests that utilize vendor test hardware. For NASA led tests, the test planning, preparation of test documentation, and test execution is overseen by the integrated test team with representatives from multiple organizations within NASA. As the NASA experts on HITL spacesuit testing, the AST ITT team is largely involved in the test planning and safety related documentation. For Axiom led tests with NASA test subjects, the integrated test team supports the testing by observing the test and overseeing the execution in regards to the suit subject safety.

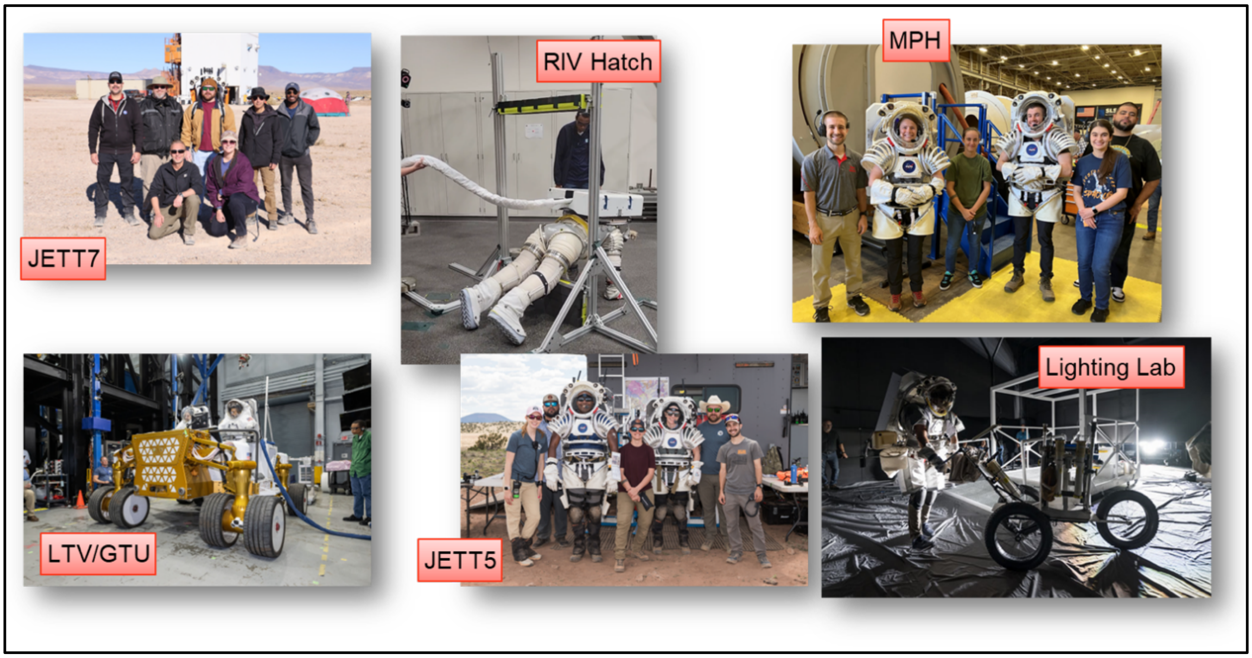


**Figure 2. Various testing supported by the Advanced Suit Team in 2024-2025.**

## A. Preparation for Task Capability Assessment

The xEVAS contract requires a Task Capability Assessment (TCA) be executed by CDR. The TCA is a NASA-led assessment of the ability of subjects from across the anthropometric range to complete tasks required in the contract mobility matrix, in addition to any other construction, repair, and science tasks that will be required on the mission. This test series is planned to primarily use NASA astronauts as test subjects and is a significant departure from testing in recent history. This testing involves the first significant evaluation of a new suit system in the past 40+ years, for a new gravity environment in the past 50+ years, and utilizes new test facilities. Most significantly, evaluation of development hardware requires a different mindset in comparison to operational testing. To prepare the TCA test subjects and astronaut office for this test series the Advanced Suit Team, along with our partners in Human Health and Performance, and the Operations Directorate constructed a test subject school.

The content of this effort was intended to mirror many of the concepts that are taught at Navy and Air Force Test pilot school, as we had contributors who had been trained in each system. The first section of the course communicated the shift required to focus on being a tester (This task is difficult; what can be improved in the system) instead of an operator (This task is difficult; I must work harder). Crew have been using a fixed spacesuit system for the past 40+ years and have learned how to most effectively utilize that system by overcoming the suit system's limitations. Those suit system limitations result in operational limitations (designing the task, the interfaces, or tools around the suit), increased training (significant effort to learn how to do a task or significant physical and/or mental preparation to enable someone to do it), and careful selection of operators (limitations on the size and fitness required for someone to successfully use the system). When evaluating a new system, crew have to re-think how they would like to use the system, how the system they are evaluating behaves, isolate and describe any offending characteristics of the system and the effects of that system and describe if and how they may be able to compensate for limitations in the system design. Finally, they must be able to translate how those adverse effects and compensations may impact the overall mission.

The second section of the test subject school course included an overview of spacesuit design characteristics and an overview of how we test spacesuits to evaluate the suit performance and the human/suit interaction. The third section reviewed historical planetary spacesuits and recent spacesuit development projects, utilizing the previously described design characteristics to discuss the pros and cons of each of the suit systems. A significant portion of the overview focused on the groundwork laid by the Advanced Apollo development programs and how system concepts and designs evolved from that foundation.

The fourth section of the course focused on the hazards associated with spacesuit testing, and how those hazards are controlled for each of the test environments that we utilize. This section also discusses the test environments we use, predominately to simulate the gravitational field that we will operate in on the moon, as well as the pros and cons of each of these test environments.

The final portion of the course is providing each of the crewmembers some experience in a planetary spacesuit through a lab fit check and in an offloaded test facility. As part of the fit check we go through multiple sizing configurations to allow the crewmember to experience firsthand what it feels like to have a suit that is too tight, too long, too short, and what the impacts on their comfort and performance are. Similarly, as part of the familiarization test in the reduced gravity environment, we evaluate multiple offload settings so the crew has firsthand experience with how the different gimbal settings can affect the way the suit feels and their performance in the spacesuit. We also utilize the familiarization test to advance the learning curve of how a planetary spacesuit feels and how to manipulate the spacesuit. The intent of this learning curve effort isn't to start learning compensatory methods of performance, but to give them experience in a different planetary spacesuit that can provide some background experience on the spacesuit and the test facility to better focus their evaluation of a new spacesuit.

### B. Elevated Suit Pressure (ESP) Testing

NASA is currently evaluating the trade space related to exploration atmospheres. The baseline plan for Artemis missions is to utilize an elevated cabin oxygen concentration to reduce the required pre-breathe down to the minimal durations. However, with elevated oxygen concentrations, an increasing number of materials, particularly softgoods, are flammable in the cabin environment. Reducing the cabin oxygen concentration requires an increased pre-breathe duration, for a given EVA suit pressure. Alternatively, if an EVA was conducted at a higher suit pressure, the pre-breathe duration can also be reduced. Elevated atmosphere testing has been in work to validate the relationship between pre-breathe time, cabin atmosphere, and oxygen concentration.

Historically, EVAs have been conducted in US spacesuits at the minimum pressure with 100 percent oxygen that can maintain normoxic oxygen levels. Increasing the pressure of the spacesuit will in turn increase the suit's stiffness, reduce tactility of the gloves, and accelerate joint wear and tear. To evaluate these factors a series of tests has been proposed, including mobility and comfort evaluations, cycle testing evaluations, hi-tempo EVA evaluations, and glove box testing. Glove box testing was completed in 2024, while the other test series are planned for later in 2025.

The glovebox test plan included the execution of multiple circuits of activities, intended to be challenging and fatiguing. The tests were conducted on different days, at two pressures (4.3 psid and 6.3 psid), with sufficient time to fully recover. The order of testing was randomized, and subjects were blinded to the glove pressure being tested. Test results showed inconclusive differences in performance and tactility between the different test days. Most test subjects did have some loss of strength, increased fatigue, and loss of dexterity with elevated pressures, but the results were inconclusive and inconsistent. Some subjects were not able to accurately identify which pressure they were operating at after the first test, but all could differentiate between test conditions after the second test.

## IV. Hardware Development and Evaluation

In support of the Advanced Suit Team, the hardware development team continues to evaluate the xPGS system as it encounters increased usage. In addition ,this team is tasked with maintaining the lab infrastructure to support buildup of newly procured hardware, and to infuse new hardware into the Advanced Suit Team's inventory. This team continues to evaluate xPGS wear as the pace of usage by the ITT increases and developing repair procedures and upgrades to maintain the readiness of the inventory. Areas of interest have included upgrades to boot axial brackets, redesign of body seal closure (BSC) segments, development of in-house fabrication techniques, verification methods for in-house axial restraint replacements, updates to suit mock-ups, and evaluations of design concepts to minimize in-suit noise.

### A. EMITS

The EMU Moisture Injection Test System (EMITS) was developed by NASA to characterize the performance of the Extravehicular Mobility Unit (EMU) sublimator's slurper. The slurper removes moisture from the ventilation loop that is generated by the crewmember during an extravehicular activity (EVA). EMITS injects moisture at a known rate into the EMU without the need for a crewmember to be inside the space suit. NASA successfully completed five qualification tests with EMITS and an EMU. Testing showed that EMITS can humidify dry EMU ventilation loop gas up to a latent load of 250 BTU/hr, which encompasses most EVAs. NASA plans to implement EMITS as a new pre-flight screening tool for new and existing EMU sublimators.

### B. Analog Suit

NASA has been utilizing the Atlas Devices ExCon suit for recent analog/field testing. These mock-ups provide realistic interfaces for the placement of visors, lights, cameras, and tools attachments. The mock-ups also provide some mobility restrictions and volumetric size to allow a more accurate evaluation of how to utilize this equipment. However, the mobility restrictions are not realistic, and field testing can be quite challenging as the crewmember must support the mass of these mock-ups. The mock-ups can weigh 80+ lbs when outfitted with tools, communication, and avionics systems. In comparison, considering the Moon's 1/6g gravity field, the advanced suit systems under development would feel lighter and with the pressurization of the suit, would self-support some of its own weight. This discrepancy translates to a negative impact to simulation quality. The PGS team has been working to reduce the weight and improve the mass management harnesses of the analog suit system to improve the usability. The most recent versions of the ExCon mock-ups have removed more than 20 pounds in structure and have real-time adjustability of the waist and shoulder harnesses to adjust the load distribution and comfort.

While this mock-up system has evolved to be more useable for analog/ground testing, the Advanced Suit Team has also proposed the development of a new analog mock-up that can be lightly pressurized, to provide a more realistic on-back mass, and more realistic mobility restrictions and joint programming. This type of mock-up could also serve as a testbed to further develop technologies for future advanced suit designs, such as lightweight structures, the use of additive manufacturing, and sizing customization - each of which would provide game-changing performance improvements, as NASA looks toward Martian exploration.

## V. Technology Development and Risk Mitigation

The commercial services procurement strategy is based on the assumption that private companies are best suited to develop human spaceflight architecture that supports both an emerging commercial market and a profit incentive beyond NASA. Meanwhile, NASA is best positioned to focus on long-term research and development, which may lack a current or future profit incentive.

Therefore, the Advanced Suit Team at JSC continues to nurture the future of suit development to enable both Artemis Sustaining Lunar evolution and future missions to Mars. xEVAS task orders are poised to provide a replacement of the EMU suit to support ISS missions through at least 2030 as well as initial Lunar EVA capability. As the Moon to Mars Program and Artemis missions progress, NASA will continue to identify and close technology gaps through research and development activities to reduce programmatic risks, enable new capabilities, and develop new technologies in support of the Moon to Mars objectives.

The notable technology development efforts for the JSC Advanced Suit Team as of FY25 are as follows:

### A. Artemis Suit Materials textile development

The Artemis III task order on the xEVAS contract focuses development on the design and fabrication of an EVA suit system for the first Artemis mission. As of February 2025, no additional task orders have been awarded for following Artemis missions. Therefore, the Artemis III EVA vendor does not have requirements for sustaining-class hardware, nor have they been incentivized to develop it. As documented in the EVA Technology Development Roadmap (ICES-2024-022), significant capability gaps remain as it pertains to sustaining class hardware for Artemis V and beyond.

One such gap is the development of an outer fabric for the Environmental Protection Garment (EPG). Notably, the xEMU government reference design baselined OrthoFabric for the outer EPG material due to the lack of a suitable replacement that met requirements and could be developed within the project schedule. The Technology Integration and Partnerships office (JSC Mailcode: DT) of the EVA and Human Mobility Program (EHP) has recognized this gap associated with sustaining EVA operations on the Lunar surface and 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 FY27. It will include custom development of a bespoke outer EPG fabric and evaluation of that fabric in environmental coupon testing, a human vacuum glovebox test and a thermal vacuum cycle test at cryogenic temperatures.

Over the past year, the project has been successful in completing significant market research on optimal fibers, yarns, structures and coatings. Initial prototypes have been developed and tested, and multiple new test capabilities have been developed, including the capability to measure tensile strength, cut resistance, tear resistance, puncture resistance, flexibility, and flex fatigue at cryogenic temperatures. For more detailed status of this project, please refer to ICES-2025-56.

### B. 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 mitigate risk and develop new technologies to enable future NASA missions. As of this writing, these efforts include the following:

- EPG textile and material development (Phase II)
- Persistently antimicrobial suit bladder materials (Phase II)
- Advanced water connectors (Phase II)
- Permanent helmet anti-fog coatings and technologies (Phase II)
- Advanced flexible formulation aerogels for Mars (Phase I)
- Cryogenic compatible materials for Lunar south pole (Phase I)
- Lightweight and dust-tolerant structures (Phase I – pending)

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.

### C. Lunar Boot Thermal Vacuum Test

Due to the unique thermal environment at the Lunar south pole, specifically permanently shadowed regions with temperature excursions as low as 48K, there are significant thermal challenges which must be addressed. One key issue is the design of the Lunar boot, which must protect both the suit and the crew from the thermal extremes of direct contact with the lunar soil at these temperatures. This challenge in part defined the design and architecture of the xEMU Lunar Boot, which includes a unique thermal insert and a design that minimizes heat transfer between the ground and the rest of the PGS.

Although the xEMU was thoroughly tested in JSC's Chamber B at cryogenic temperatures, this testing was not focused specifically on the boot, and it was determined that boot-specific testing would not only provide additional insight to the xEMU Lunar Boot performance and thermal model, but perhaps more importantly, develop a test facility and procedure that the xEVAS vendor for Artemis could leverage to validate their boot's performance and requirements. Therefore, a test of the xEMU Lunar boot at the JPL's Citadel chamber was completed in FY25 which provides both xEMU government reference design performance data and xEVAS vendor risk reduction. This testing was completed at temperatures as low as 50K and will be detailed in a future ICES paper.

### D. Lunar EVA Dust Mitigation testing

The Advanced Suit Team is pursuing multiple collaborative technology developments across JSC and NASA. In one example from FY25, the team provided PGS test articles comprised of boots, gloves, and EPG layups, to support testing of the Lunar Electro-Static Discharge (ESD) and Dust Mitigation (LEDM) dust removal tool at JSC's Energy System Test Area vacuum chamber. In this test, PGS test articles were fabricated and mounted to a fixture, and the LEDM tool, controlled by a robotic arm, used ionized gas to remove the dust from the surface in a vacuum environment. Dust removal (mass) and x-ray and optical imaging were used to measure dust removal performance.

### E. Space Act Agreement with Nike Innovation

NASA and the Advanced Suit Team pursues strategic collaboration through various mechanisms, including Space Act Agreements. In FY25, the team spearheaded a non-reimbursable Space Act Agreement with Nike, Inc and their Innovation Team with the goal of leveraging Nike's design and prototyping expertise to improve xEMU Lunar Boot sizing inserts as well as subject-worn ancillary items.

### F. PGS Technology Development Roadmap

In collaboration with the Technology Development and Partnerships Office of EHP, the Advanced Suit Team has revised the Pressure Garment 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 update is available in ICES-2025-061, *NASA Extravehicular Activity Technology Roadmaps for Exploration – 2025 Status (Ref)*

## VI. Conclusion

The Advanced Suit Team at JSC continues to position itself strategically to best leverage its extensive knowledge and expertise to close EVA gaps, technical risks, develop new technologies, and enable future NASA missions. We continue to pursue new opportunities to ensure that NASA is ready to meet the needs of future Artemis and Mars missions.

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