NASA Advanced Space Suit Pressure Garment System Status and Development Priorities 2023

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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. ICES papers in 2022 detailed the design of the xEMU pressure garment components. This paper outlines the design updates to the xPGS since that time. More notably, 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 transition from xEMU development and testing, to supporting the Exploration Extravehicular Activity Services (xEVAS) vendors will also be 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

ABF	=	Anthropometry and Biomechanics Facility
ANSUR	=	Anthropometric Survey of US Army Personnel
BLVD	=	Boot Leg Vent Duct (Assembly)
DVT	=	Design Verification Testing
EMU	=	Extra-Vehicular Mobility Unit
EVA	=	Extra-Vehicular Activity
HITL	=	human-in-the-loop
HUT	=	Hard Upper Torso
ISS	=	International Space Station
LCVG	=	Liquid Cooling and Ventilation Garment
NASA	=	National Aeronautics and Space Administration
PDR	=	Preliminary Design Review
PGS	=	Pressure Garment Subsystem
PLSS	=	Portable Life Support System
PTRS	=	Project Technical Requirements Specification
ROM	=	Range of Motion
xEMU	=	Exploration Extra-Vehicular Mobility Unit
xINFO	=	Exploration Informatics Sub-system
xPGS	=	Exploration Pressure Garment Sub-system

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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 2025. The Advanced Space Suit Pressure Garment Technology Development team ("Advanced Suit Team") at NASA's Johnson Space Center continues to work to this mission. The Exploration Extra-Vehicular Mobility Unit, or xEMU, has been the primary focus of the Advanced Suit Team for the past several years. Delivery of multiple full xEMU pressure garment (xPGS) assemblies and Design Verification Testing (DVT) were completed in the summer of 2022. Multiple publications have recently documented the xPGS assembly (REF) and components (REF) design, as well as preliminary results from DVT (REF). Subsequently, mobility and cycle testing campaigns were completed in reduced gravity using the Active Response Gravity Offload System (ARGOS) at Johnson Space Center (JSC). In addition, training runs at the Neutral Buoyancy Laboratory (NBL) and other evaluations have provided significant meaningful information about the xEMU suit's performance.

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. In addition, 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.

II. Team Mission

Over the past five years, the Advanced Suit Team at JSC has managed through a lot of change, from working a demonstration mission of the xEMU at the ISS, to initiation of a Government-Furnished Equipment (GFE) effort for the Artemis Program suit, to transition of Artemis suits to a commercial services contract. With the xEVAS contract now underway with awarded task orders and a more firm outlook of the Artemis program in general, it makes sense to orient the reader to the mission and strategy that the team is employing to best support that mission.

The NASA Advanced Suit Team's mission is to assess and mitigate suit-related risks to NASA missions. These risks include both short term, specific to a single EVA, and long term, beyond not just the current program but beyond the next one as well. This work includes mitigation of very specific risks, but also applies more broadly, such as system level testing, integration, and technology development efforts. In that context and in retrospect, the xEMU project squares firmly with that mission in that it matured a new suit platform to help position the xEVAS vendors for success.

III. xPGS

The xEMU project evolved over time. In 2018, the xEMU Demo pressure garment architecture was presented[1], which included a new HUT, Shoulders, Helmet, and Extra-Vehicular Visor Assembly (EVVA), while reusing the EMU lower torso, arms, gloves, and boots. The xEMU Demo project covered the manufacturing of a single PLSS and Pressure Garment Subsystem (PGS) and a single flight demonstration on the ISS. The project's intent was to conduct a flight demonstration of new technologies and then transition fleet manufacturing and sustaining to a prime contractor to replace the EMU. However, with the new direction in 2019 to put boots on the moon by 2024, the xEMU project was identified as the best path to manufacture suits for the initial lunar mission, projected to occur near the lunar south pole. As a result, the xEMU project transitioned into a multiple program flight project, that included development of both a suit for the ISS and for the first Artemis lunar surface mission. This transition to a multi-program, multi-destination system was a significant change in project scope and requirements which resulted in changes to the xEMU's architecture. These changes included improved lower torso mobility, Lunar boots that meet challenging thermal requirements of the permanently shadowed regions (PSR) of the Moon, a new environmental protection garment (EPG) for dust protection, and enhanced

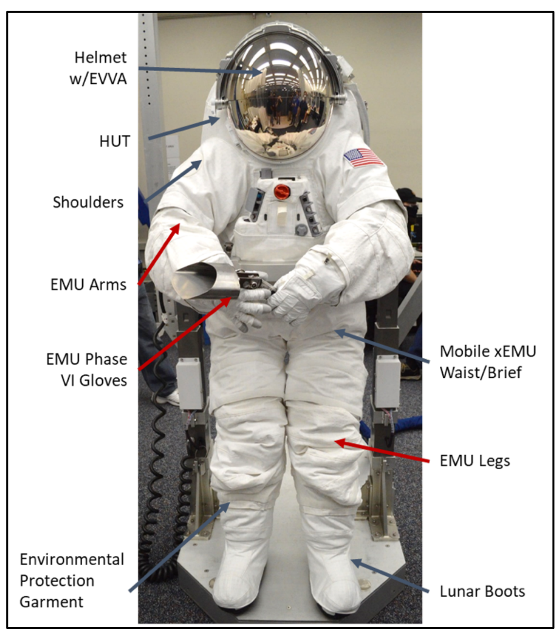

Figure 1: xPGS Design Overview

cycle life performance over the needs of the ISS. The xPGS DVT unit, the pressure garment of the xEMU is shown at right in Figure 1. For much more detail on the design of the xPGS and the components that comprise it, the reader will refer to the various manuscripts published in 2022 (REF).

A. xEMU Design Verification Testing (DVT)

One of the lessons conveyed from Gemini, Apollo, and EMU suit programs was the importance in building and testing a development unit before attempting suit certification. The xEMU project therefore was conceived including a development unit which would be evaluated in Design Verification Testing (DVT). DVT is an opportunity to take the prototype hardware through select certification-like tests to reduce risk that the design will pass certification. Some of the highest priority subsystem tests focused on evaluation by multiple subjects from across the anthropometric range against requirements for mobility, fit and comfort, and cycle life. For the xPGS team, DVT was comprised of Mobility testing, Cycle (Life) testing, and NBL testing as well as myriad PGS component-level tests.

Mobility testing was executed in both 1G and 1/6G using ARGOS and was completed in May 2022. The test was composed of XXX subjects completing a battery of XXX tasks. Subjective and objectively metrics for mobility, fit and comfort were collected. Cumulatively, the lessons learned from DVT Mobility are below. More detail on mobility testing is available in another report, ICES-2023-XXX, Mobility Test for xPGS (REF).

- The xPGS suit was able to satisfactorily provide the mobility to complete all necessary tasks across the entire subject pool
- A change to the EPG architecture was required due to mobility restrictions induced by the full EPG ply combined with the coverage required for dust protection
- For planetary tasks such as kneeling to pick up an object, the ARGOS platform induces a significant effect on mobility and reach
- Mobility testing provided meaningful data about xPGS performance, and also valuable experience on the xPGS hardware, ARGOS test environment, and test protocol that was carried into DVT cycle life testing.

Cycle life testing of the xPGS was executed in 1/6G using ARGOS and was completed in September 2022. The test was composed of XXX subjects completing a routine of XXX tests. The routine was completed a number of times that correlated to twice the total number of joint and mechanism cycles as would be expected in a typical Artemis mission. More detail on the specifics of the xEMU cycle model and the results of the cycle testing are available in ICES-2023-XXX, Cycle Test for xPGS. For the purposes of a high-level summary, DVT Cycling lessons learned are as follows:

- The xPGS was able to complete all necessary cycles and demonstrated general acceptability for future Lunar missions, correlating to approximately XXX Lunar EVAs.
- Existing EMU glove designs are inadequate in meeting demands of Lunar cycling
- The water and vent loop connectors that connect to the Liquid Cooling and Ventilation Garment (LCVG) cause persistent wear issues when combined with a walking lower torso
- All xPGS components received some wear or damage which was documented and in many cases, mitigated
- Cycle testing provided meaningful data on xPGS cycle life performance which has been made available to the xEVAS vendor partners

NBL and other non-DVT 1-G testing is currently underway by the xPGS xEVA test/training team to aid in evaluation of ISS, HLS, LTV, and other vehicle and human surface mobility asset interfaces. Evaluations include xEVA tools/support hardware. These test events are also intended to provide crew and other support organizations with training and familiarity with the xPGS, and to provide additional design data to the xPGS team.

B. xPGS Updates for FY23

Subsequent to the most recent xPGS overview published in 2022, there have been several updates and modifications to xPGS hardware.

Most notably, the Lunar boot received a major expected update that added EPG interfaces, dust proofing, boot tightening using a boa lacing system, and other refinements toward a more flight-like design. Due to the low state of maturity for the Lunar boots, which must survive PSR temperatures as low as -370°F [-223°C], the original procurement strategy was devised as a two-stage effort with an initial delivery and assessment in early DVT, and feedback to the vendors with a design iteration to increase maturity in late DVT. The updated boots from each vendor are shown below in Figure 2.

Figure 2: Phase II David Clark (left) and Final Frontier Design (now Paragon, right) xPGS Boots

C. xPGS Lessons Learned

As of this publication, the xEMU is by far the highest maturity EVA suit development since the Enhanced EMU. In addition, considering the xPLSS, xPGS, ISS and Lunar configurations, tools, and advanced informatics, the xEMU is the most comprehensive suit development ever undertaken. Currently, the xPGS team is supporting multiple test series with the xPGS suits, including thermal vacuum chamber testing. Throughout DVT, post-DVT NBL training, and other testing, the team continues to gain experience with the xPGS hardware. We continue to document these lessons for posterity and to share with the xEVAS vendor partners, who to a large extent are leveraging the xEMU designs in their architecture.

D. Existing Risks and Risk Mitigation Plans

IV. xEVAS

The EMU and Apollo suit developments were accomplished on large government contracts, initially competed and subsequently awarded to teams of private companies responsible for meeting the levied technical requirements, deliverables, and schedule on a cost-plus contract. These companies engineered, fabricated, assembled, tested, and certified the suit at the assembly level and then delivered that hardware to NASA. In contrast, the xEMU project was originally devised and thus far, executed as a government-furnished equipment (GFE) effort. NASA-led teams at JSC conducted much of the engineering and design, in tandem with myriad contractors and vendors on a component-level or part-level basis. The NASA-led teams were also responsible for assembly, testing, and certification. This means that the xEMU project is a significant departure from every previous EVA suit development. At the time, the capability of NASA in-house expertise as well as limited appetite for, and funds available to, award large contracts for EMU replacement and early Artemis architecture were significant factors in pursuing this GFE procurement strategy.

However, as the Artemis program matured and gained inertia, more funding became available as allocated from congress. The award of the Human Landing System (HLS), coupled with the recent successes in the Commercial Cargo and Crew programs, were catalysts for a change to xEMU procurement strategy. Over the summer of 2021, a Request for Information (RFI) and Request for Proposal (RFP) were posted to solicit responses by potential vendors or vendor teams to provide an ISS EMU suit replacement and the Artemis lunar suit as a service, wholly developed, certified, and owned by the vendor. Under this solicitation, 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 itself but also support training, maintenance, sustaining engineering, etc. that historically fall under NASA purview or are executed on post-delivery sustaining engineering contracts. Under the xEVAS solicitation, the complete xEMU design, hardware, 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.

As of 2023, task orders have been awarded to two xEVAS industry partners. Axiom Space was awarded a task order in September 2022 to deliver the EVA system for the Artemis III mission. In December 2022, Collins Aerospace was awarded a task order to develop an EVA system for the International Space Station and complete a Critical Design Review in pursuit of that mission.

The Advanced Suit Team is currently supporting both task orders through support mechanisms identified in the xEVAS contract. The first support mechanism is called "Insight"; in this role, NASA personnel ensure that vendor development plans, designs and deliverables are consistent with contract requirements and will ensure NASA mission success. Due to providing Insight to both vendors and the high number of deliverables requiring review at one time, the advanced team has approximately three team members fulfilling the xEVAS Insight role in addition to other team responsibilities.

The second support mechanism is called "Collaboration". In this role, NASA personnel augment the xEVAS vendor teams to aid in development and hardware certification, as well as gain detailed understanding of the hardware design to facilitate additional support in the future such as risk mitigation activities.

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.

V. Current Technology Development Efforts

Underpinning 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. Implicit to this assumption is that in contrast, the government is best positioned to conduct longer-term research and development which does not currently have or may never have a profit incentive. Short term, the xPGS team is focused on supporting xEVAS.

Long term, the advanced suit team at JSC continues to look toward the future of suit development to be ready for what comes next. xEMU or xEVAS only gets us so far – a replacement of the EMU suit to support ISS missions through 2030, and initial Lunar EVA capability. Experience gained from using the initial Lunar suit may drive NASA to complete or oversee development to enhance performance or operations. Sustaining Lunar operations at a habitat may require significant improvements over the initial Lunar suit design – to provide longer-term durability, to facilitate interface with new lunar surface assets, and to improve operational efficiencies. Other exploration destinations of the future – Mars, Phobos/Deimos, or asteroids, may require different designs and materials.

With these goals in mind, below are the significant technology development efforts occurring on the team as of FY23.

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

While the xEVAS vendor for Artemis is responsible to deliver Lunar gloves and to meet associated technical requirements, they have only been awarded one mission as of this writing. This does not necessarily drive them to meet longer-term durability requirements that would be associated with a sustaining presence at the South pole of the Moon. The NESC has 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 risk mitigation of having acceptable gloves to support sustaining Lunar operations under the Artemis program.

This project started in June 2022 and is currently scheduled to be completed by December of 2023. It includes extensive material testing, dust testing, and thermal testing to address the specific challenge of Lunar PSRs. While results have not yet been reported and are still preliminary, this project will provide 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.

B. EHP/DT Artemis Glove formulation

The Technology Development and Partnerships office (JSC Mailcode: DT) of the EVA and Human Surface Mobility Program (EHP) has also recognized the risk associated with sustaining EVA operations on the Lunar surface as it pertains specifically to gloves and glove environmental protection garments (EPG). In that context, EHP has funded the Advanced Suit Team with an initial formulation phase for the first quarter of FY23 to develop a project plan to fully address this risk over the coming several years. The specifics of this project plan are still preliminary, and the full project has yet to be approved.

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
- Electrochromic visor materials
- Persistently antimicrobial suit bladder materials
- Advanced water connectors

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.

VI. Conclusion

The advanced suit team at JSC continues to adapt to the changing landscape of exploration missions and commercial services. While it continues to be a dynamic time which will likely continue for many years to come, it is also a time for opportunity for those organizations that are able to adapt to that change. With that in mind, the Advanced Suit Team continues to position itself strategically to best leverage its extensive knowledge and expertise on pressure garment technologies. We look forward to what the next decade brings.

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