

Advanced Technology Infusion into Spacesuit Systems

Cinda Chullen¹

*NASA Johnson Space Center, Houston, Texas, 77058 & Stevens Institute of Technology,
Hoboken, NJ*

Iser Pena², Kaushikk Ganesan³, and Dr. Hao Chen⁴

Stevens Institute of Technology, Hoboken, NJ

Advancement in technology drives our future. The successful implementation of a technology drives its possibilities. The National Aeronautics and Space Administration (NASA) has invested in numerous technologies that have proved to be successful. The desire is to learn from those successes. For a technology to evolve, become a reality, and infuse into NASA's missions, a compilation of success-oriented factors must exist for the technology to reach fruition. Understanding these factors could help decrease the complexity of technology infusion and bridge the gap between technology developers and system integrators. The knowledge gained could facilitate the design, development, test, and infusion of a technology to be more effective and efficient. Successful technology infusion is complex and can be even more daunting when advanced technologies are infused into complicated systems. NASA, industry, and academia desire to understand the infusion process, along with measuring the success of infusing an advanced technology into a complex system. This paper focuses on complicated systems that necessitate successful infusion of technologies. These systems include NASA's spacesuits used for extravehicular activity, including the Apollo Extravehicular Mobility Unit (EMU), the Shuttle/International Space Station EMU, and the Exploration EMU (xEMU) architectures. Several life support technologies will be addressed in the xEMU. Those technologies will be discussed, along with a methodology for assessing infusion pathways. The infusion pathways of these life support technologies into spacesuit architectures can form the benchmark for technology infusion into other architectures for lunar and Martian surfaces. The spacesuit system architectures as case studies can provide the foundation of technical knowledge to help NASA and industry's project managers and system managers integrate advanced technologies more effectively and efficiently.

I. Nomenclature

<i>BSLSS</i>	= Buddy Secondary Life Support System
<i>CM</i>	= crew member
<i>CMP</i>	= Command Module Pilot
<i>CO₂</i>	= carbon dioxide
<i>DVT</i>	= Design, Verification, and Test
<i>EHP</i>	= Extravehicular Activity and Human Surface Mobility Program

¹ Exploration Extravehicular Mobility Unit Component Manager, Space Suit and Crew Survival Systems Branch, Crew and Thermal Systems Division, NASA Parkway, Houston, TX 77058/EC5 & Ph.D. Candidate, School of Systems & Enterprises, Stevens Institute of Technology, Castle Point on Hudson, Hoboken, NJ 07030.

² Graduate Research Assistant, School of Systems & Enterprises, Stevens Institute of Technology, Castle Point on Hudson, Hoboken, NJ 07030.

³ Undergraduate Research Assistant, School of Systems & Enterprises, Stevens Institute of Technology, Castle Point on Hudson, Hoboken, NJ 07030.

⁴ Assistant Professor, School of Systems & Enterprises, Stevens Institute of Technology, Castle Point on Hudson, Hoboken, NJ 07030, AIAA Member.

<i>EMU</i>	= Extravehicular Mobility Unit
<i>EV</i>	= extravehicular
<i>EVA</i>	= extravehicular activity
<i>EVAS_SAT</i>	= Extravehicular Activity System Sizing Analysis Tool
<i>HLS</i>	= Human Landing System
<i>HUT</i>	= hard upper torso
<i>ISS</i>	= International Space Station
<i>IVA</i>	= intravehicular activity
<i>JSC</i>	= Johnson Space Center
<i>LCVG</i>	= liquid cooling and ventilation garment
<i>LTA</i>	= Lower Torso Assembly
<i>NASA</i>	= National Aeronautics and Space Administration
<i>OPS</i>	= Oxygen Purge System
<i>PLSS</i>	= Portable Life Support System
<i>PSA</i>	= Pressure Suit Assembly
<i>RCA</i>	= Rapid Cycle Amine
<i>RCRS</i>	= Regenerable CO ₂ Removal System
<i>SERFE</i>	= SWME Express Rack Flight Experiment
<i>SN</i>	= Serial Number
<i>SSA</i>	= Space Suit Assembly
<i>SWME</i>	= Suit Water Membrane Evaporator
<i>TRL</i>	= technology readiness level
<i>US</i>	= United States
<i>xEMU</i>	= Exploration Extravehicular Mobility Unit
<i>xEVAS</i>	= Exploration Extravehicular Activity Services
<i>xINFO</i>	= Exploration Informatics
<i>xPGS</i>	= Exploration Pressure Garment System
<i>xPLSS</i>	= Exploration Portable Life Support Subsystem

II. Introduction

One of the most complex systems ever developed is a spacesuit. Its function is to keep an astronaut (crew member (CM)) or cosmonaut alive and to do useful work. Spacesuits have been designed for various purposes throughout multiple programs in the United States (US) including Mercury, Gemini, Apollo, Space Shuttle, and the International Space Station (ISS). These spacesuit assets at the National Aeronautics and Space Administration (NASA) are shown in Figure 1. The most complex US spacesuits are those that have been designed for extravehicular activity (EVA) or spacewalks. What makes them complex is that they are essentially a spacecraft with very specific technologies to protect the CM. EVA spacesuits allow the CM to go outside a space vehicle to perform their work. The EVA spacesuits

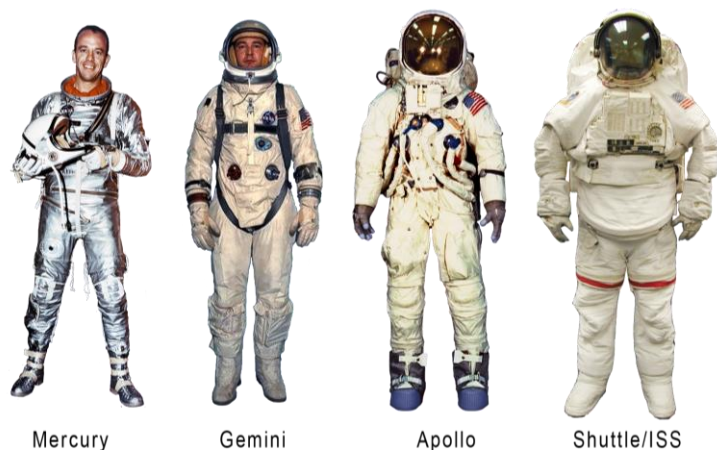


Figure 1. Mercury, Gemini, Apollo, Shuttle, and ISS
(Image created by Jeannie Corte)

of interest in this paper include the Apollo Extravehicular Mobility Unit (EMU) and the Shuttle/ISS EMU shown in Figure 1, along with the Exploration EMU (xEMU) shown in Figure 2. The EMU, used for the Space Shuttle Program, was enhanced to use on the ISS. The EMU has essentially become a symbol for NASA, and now NASA will consider a new spacesuit design architecture for missions to the moon and beyond.



Figure 2. xEMU assembled
(Image by NASA)

III. EMU Evolution

NASA's spacesuits have met the needs for human space flight by facilitating CMs to walk on the surface of the moon, repair the solar panel on Skylab, inspect critical components outside the Space Shuttle, build the ISS, capture satellites, repair the Hubble Space Telescope, and perform many other critical jobs during the history of human space flight.[1]

The EMU has evolved from Apollo to the Space Shuttle to ISS, and now to the xEMU. Since the first use of the Apollo EMU on July 20, 1969, versions of the EMU have been used for over 50 years.[2] The EMU was designed to perform an EVA or spacewalk, without an umbilical, as previously used for the Gemini Program. It evolved into the design of the Apollo EMU with a portable life support system (PLSS) worn like a backpack, which allowed Neil Alden Armstrong and Dr. Edwin E. "Buzz" Aldrin, Jr. to perform the first lunar EVA, without an umbilical, and be the first two humans to set foot on another world.[3] Since Apollo, the EMU foundational design has evolved, met the needs of the Space Shuttle, and sustained the ISS EVA capability for over 40 years. It is evident that the EMU a critical part of crewed space mission operations. However, to have sustainability on the moon, an infusion of technology is greatly needed.

A. Apollo

On May 25, 1961, US President John Fitzgerald Kennedy announced the goal of reaching the Moon by the end of the decade.[2] The Apollo Program became a national priority as a continuation of the Mercury missions.[4]

The US entered a space race with the Soviet Union without having a design, plan, and understanding of the challenges ahead. In the early days of the Apollo spacesuit program, no one knew how the spacesuit life support would be designed or how much life support would be needed. It would be the extravehicular (EV) mission metabolic profile of the CM that would drive the design of the PLSS. Key parameters influencing the PLSS design were oxygen consumption, carbon dioxide (CO₂) removal, heat removal, battery size, systems weight, and volume. A final system metabolic requirement was determined as a 1,204 Btu/h (303 kcal/h) average and a 2,000 Btu/h (504 kcal/h) peak metabolic load after a year into the program. The iterations of the metabolic load caused changes in the suit design. Because the PLSS technologies were unavailable during the 1962 timeframe, the Apollo suit design required invention and development.[2]

As part of Apollo's development of the first US spacesuit prototype, a suit system was developed that could meet the requirements of a space application reliably and efficiently. The Apollo spacesuit system included a spacesuit

Pressure Suit Assembly (PSA), which was an intravehicular activity (IVA) suit to support launch and landing. The PSA was also used to combined with a PLSS to form the spacesuit for EVA, known as the Apollo EMU. Until Apollo's EMU, pressure suits lacked autonomous EVA life support and extensive mobility.

During the Apollo planning, NASA organized the space suit systems into three categories: Blocks I, II, and III. The Blocks are identified below:

- Block I included suits for the initial flights that had no Lunar Module and no EVA capability. (1965-1967)[5]
- Block II included EVA suits and the Lunar Module (1969-1972)[5]
- Block III was designed for extended orbital operations. These missions were eventually canceled. (1972-1975)[5]

Block I was awarded to the David Clark Company, which did not include EVA suits. The Apollo EVA suits, the Apollo command, and service module would need more time to confirm safety measures for humans.[2]

During Block II, Apollo 7 through 17 missions occurred. The Apollo EMU development for Block II was a modular system consisting of two configurations. One configuration was the EV suit for the lunar module crew. This suit had an A7L-type PSA, a PLSS, and an Oxygen Purge System (OPS) (backup life support), which along with gloves, lunar boots, and a visor assembly, became the EV suit system. Likewise, this modular system without accessories served as the launch and entry support suit. The second configuration was the Command Module Pilot (CMP) suit. The CMP suit was only the PSA and it differed from the EV suit – it had only one pair of life support connectors, no arm bearings, and minimal insulation in the cover garments. During these missions, the EV suit also had a primary life support capability of 6 hours and a backup life support capability of 30 minutes, with an operating pressure of 3.7 psi (25.5 kPa).[5]

Apollo 11 through 13 missions included the initial lunar landing missions. Several improvements were made to the Apollo EMU. A camera was added, controls were updated, and the helmet was enhanced. The chest-mounted remote-control camera was added to facilitate lunar photography. Additionally, the controls were revised to make them easier to use with pressure gloves. To prevent condensation in the helmet and to control light reflection better, the lunar EV visor assembly on the helmet received an outer shell and thermal outer cover. To facilitate crew identification, Apollo 13's mission commander's suit included red stripes on the knees, shoulder, and helmet.

Apollo 14 had a Buddy Secondary Life Support System (BSLSS) as an emergency device. This system was a 2.5 m (8 ft) liquid-cooled umbilical. The BSLSS provided a CM with a failed backpack needed life support. It activated the OPS and drew cooling water from the crewmate's healthy backpack until the CM could return to the lunar module.

In 1970, Apollo 15 through 17 missions, the EV configuration consisted of an Apollo A7LB side/mid-entry PSA. These missions involved extensive scientific investigation of the moon on the lunar surface and from lunar orbit and supported 13 EVAs totaling 124.6 man-hours in space. The A7LB pressure suits featured a different entry zipper orientation, neck and waist joints, lower torque shoulder joints, improved gloves, and a redesigned breech to improve walking performance. Additionally, the A7LB CMP PSAs were retrofitted with rear entry like the A7L.[5]

Block III was expected for Apollo 18 and later missions. This block was dedicated to long-duration missions and more advanced EVA suits before the 1970s. However, this block was later canceled because of adjustments in NASA's strategic program and other factors, yet it was the impetus that sustained Space Shuttle flights for nearly 30 years, as well as the next generation of US spacesuits in the early 2000s. [5]

Overall, the Apollo Program laid the foundation for spacesuits with life support systems for years to come. These spacesuit systems sustained CMs on EVAs throughout the Shuttle program and throughout the ISS program.

B. Space Shuttle/International Space Station Extravehicular Mobility Unit

The EMU was designed in the early 1970s, and it was demonstrated on the maiden flight of the Space Shuttle Challenger (STS-6) in 1983.[1] STS-6 was the sixth launch of the Space Shuttle in the program's lifespan (1981 to 2011).[2] The EMU was designed to meet the demands of the Space Shuttle Program and to perform EVAs or spacewalks. Since then, the EMU has facilitated astronauts to save Skylab, repair the Hubble Space Telescope, construct the ISS, retrieve satellites, and examine exterior components of a Space Shuttle. The EMU remains in use on the ISS, culminating in almost 40 years of spacewalks. This demonstrates that the EMU has become the true workhorse of EVAs for NASA.[3]

The EMU's integrated assembly consists of two main subsystems: the Space Suit Assembly (SSA) and the PLSS. The EMU is designed to provide environmental protection against extreme heat of up to 250 °F, extreme cold as low as -250 °F, micrometeoroids traveling up to 17,000 miles per hour, and space radiation.[4] Furthermore, the EMU is built to provide mobility, life support, and communicational abilities to the CMs during spacewalks. The suit was designed and manufactured in three main sizes for the hard-good components, which can be assembled in

combinations to fit the CMs.[5] The suit is integrated and equipped component by component. The entry mechanism for the suit is analogous to putting on pants followed by a shirt. The Lower Torso Assembly (LTA) is donned like pants. Next, the hard upper torso (HUT) is donned like a shirt. After the LTA and HUT are connected, the gloves and helmet are donned.[5] The EMU is currently the only operational pressurized flight suit in the US that allows the astronauts to perform space walks in zero gravity. Although the EMU was not built for lunar space exploration, the EMU's PLSS drew heavy inspiration from the Apollo spacesuit technologies employed to explore the surface of the moon in the late 1960s and early 1970s.[3]

The life support technologies that formulated the Shuttle/ISS EMU's PLSS will form the benchmark for technology infusion into architectures for lunar and Martian surfaces. Just as the Shuttle drew inspiration from the Apollo EMU, the reverse will occur as the xEMU (or commercial spacesuits) draws inspiration and lessons learned from the ISS EMU. However, now the purpose has shifted to sustaining a presence on the lunar surface. This will create new challenges with the opportunities for new spacesuit technologies.

IV. A Spacesuit Architecture Case Study

As NASA plans for missions to the moon and Mars, a different kind of spacesuit will be needed. One that tolerates gravity and dust. The new spacesuit will need to have increased mobility as well as sustainability. For the last 15 years, NASA has been developing a next-generation spacesuit, which has led to the xEMU design at the Johnson Space Center (JSC) in Houston, Texas. The xEMU is shown in Figure 2. This is the first new NASA spacesuit designed in over 40 years.

The xEMU was designed to be safe, reliable, and provide a high degree of performance capabilities. The xEMU incorporates a culmination of lessons learned from NASA's historical spacesuits and incorporates an array of new technologies and innovations with the objective for a mission on the lunar surface. The xEMU is unlike the previous EMUs; it is a rear entry spacesuit that targets more mobility and flexibility of movement. The xEMU marks a new era in spacesuits incorporating innovations and technology advancements, as well as lessons learned from the past. Figure 3 identifies several innovations in the xEMU.[6]

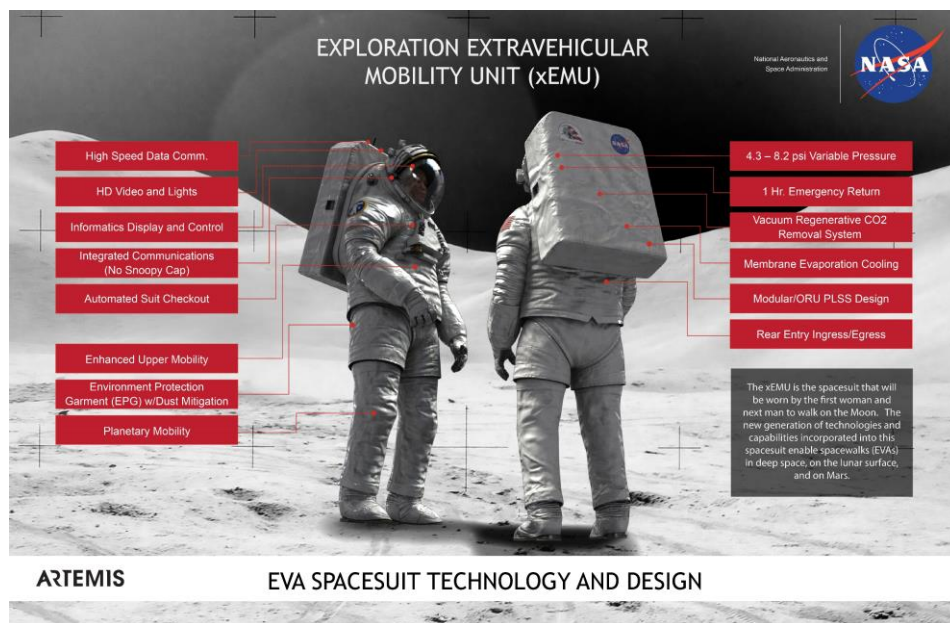


Figure 3. Exploration xEMU (Image by NASA)

The xEMU resulted from decades of lessons learned, along with decades of technology development. However, it was a comprehensive and far-reaching schematic study that influenced and shaped the design of the xEMU and facilitated the infusion path for game-changing technologies. NASA engineers meticulously evaluated the PLSS schematic and technology options, which would lay the foundation of the baseline architecture. The schematic study was two phases that lasted about 2 years. Overall, there was an industry study and an academic study that occurred independently. Thereafter, an expert review of both studies resulted in a down select of the technologies.[7]

A success-oriented PLSS schematic resulted from the schematic study that could support several mission architectures.[8] Many years of technology development ensued thereafter that was facilitated by funding from multiple NASA programs over 15 years. This funding catapulted these technologies into an infusion path of development resulting in the current Exploration Portable Life Support Subsystem (xPLSS) design.

Figure 4 shows how the xEMU design is subdivided into three major subsystems. The subsystems include the xPLSS, Exploration Informatics (xINFO) Subsystem, and Exploration Pressure Garment System (xPGS). Each subsystem is divided into groupings and components. Each grouping is subdivided into individual components. Figure 5 is an example of how the groupings are divided into components. An understanding of how the xEMU is designed can lead to a better understanding of technology infusion. Therefore, the xEMU is an excellent candidate for a spacesuit architecture case study for this research.[9]

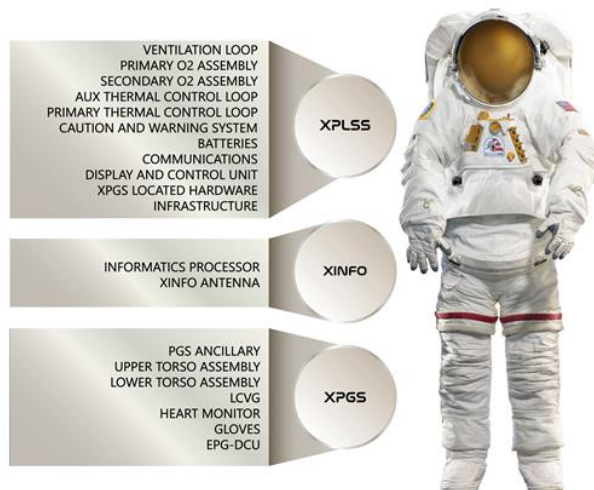


Figure 4. xEMU design. (Image by Jeannie Corte)

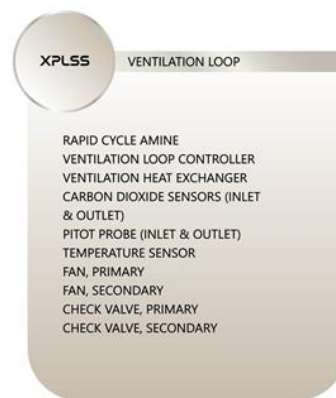


Figure 5. Example of a grouping divided into components. (Image by Jeannie Corte)

The xEMU is comprised of over 90 individual components. Ultimately, this research will assess the 90 components. However, this paper introduces advanced technology infusion into a spacesuit system and highlights two of the game changing technologies in the xEMU, namely the Rapid Cycle Amine (RCA) and the Suit Water Membrane Evaporator (SWME).

A. Rapid Cycle Amine

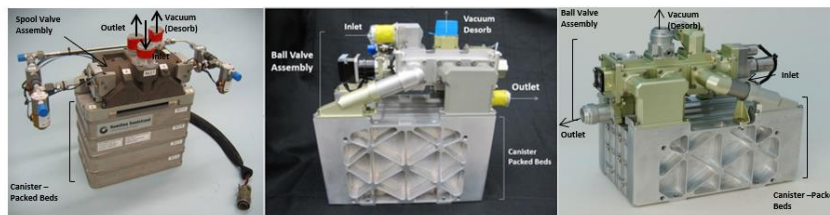
Innovative technology was incorporated into the xPLSS to facilitate longer duration operation of the xEMU. The RCA technology was one of the more significant innovations to the xEMU. The RCA component is targeted to eliminate the need to logistically change out the CO₂ collection canister, as was done in the EMU. The RCA component is a vacuum-regenerable technology for CO₂ and humidity control that employs a solid amine sorbent in an alternating 2-bed adsorbing and desorbing configuration. One bed adsorbs CO₂, while the other bed desorbs the CO₂ to vacuum. The current EMU technology employs a “single use” adsorbent (lithium hydroxide or metal oxide), which increases operational logistics and costs. The RCA technology offers significant advantages as a result of the regeneration capability of the technology. During the schematic study, the RCA technology was deemed to be at a technology readiness level (TRL) 5.[10] This TRL was based on previous development of the Regenerable CO₂ Removal System (RCRS) developed at JSC for the Space Shuttle Orbiter, as part of the Extended Duration Orbiter Program. Although the amine was different (polyethylenimine) than that used in the RCA (SA9T), the similarity was sufficient to proceed with the development of the RCA for spacesuit infusion.[7][11]

During the schematic study, the areas of development concerns for the RCA were well understood. These concerns (e.g., cycle time, adsorption rate, and regeneration efficiency) were factored into a healthy progression of technology development and testing thereafter. The progression of the technology is shown in Figure 6. The recommendation

from the schematic study was significant in setting the course of action for the RCA development. The RCA proceeded to be developed to a point whereby it became a viable component for the xPLSS.[12][13][14]

RCA Units 1.0, 2.0, & 3.0

The RCA is a prototype solid amine-based system designed to continuously remove CO₂ and H₂O from a flowing ventilation stream via a two-bed amine based, vacuum-swing adsorption system.



- RCA 1.0 designed in 2007
 - Tested component level 2/10- 4/11, 8/11-9/12
 - Tested PLSS 1.0 Breadboard 4/11-8/11
 - RCA 2.0 designed in 2012
 - Tested in PLSS 2.0 FY14 -FY15
 - RCA 3.0 designed in 2015
 - Controller integration in 2015
 - RCA 3.0 in incorporated into xEMU PLSS 2.5
- RCA cylindrical prototypes were tested from 6/10-4/11

Figure 6. RCA Units 1.0, 2.0, & 3.0 (Image by NASA)

B. Suit Water Membrane Evaporator

Regulating temperatures in the hostile environment of space has been vital to ensure survival of CMs during spacewalks. Even if the EMU were built to handle extreme temperatures for extended periods, the human body was not. Therefore, NASA has been involved in the development of technologies like the SWME for over a decade. The SWME component is shown in Figure 7.[15]

Water quality issues have caused several failures for NASA. For example, one of these issues occurred in EVA 23, when water leaked into the CM's helmet during the EVA. Water seeped into the vent loop, which was caused by a blockage in the spacesuit water separator.[16] NASA has pursued development efforts to decrease the sensitivity to water quality issues, increase the life of the EMU on the ISS, reduce maintenance, increase reliability, and increase robustness.[17] Therefore, it was vital that NASA pursue the advanced development of the SWME component.

The SWME's primary function is to reflect heat from a spacesuit and provide cooling to both the CM and the avionics. This function is accomplished by circulating the suit cooling water through microporous, hydrophobic tubes in the SWME. Liquid water is always running through the tubes, but a minute amount of water is evaporated and escapes through the tube pores to be exhausted in the space vacuum, allowing for heat removal through evaporation. Additionally, the SWME allows for degassing the thermal control loop.[18]



Figure 7. SWME (Image by NASA)



Figure 8. SERFE Flight Unit (Image by NASA)

The SWME was tested in microgravity through extended operation on the ISS by the SWME Express Rack Flight Experiment (SERFE). The SERFE Flight Unit (S/N 1001) is shown in Figure 8, before launch. SERFE contained a dual locker format experiment with a high fidelity xEMU cooling system mounted in a vacuum chamber, along with a liquid cooling and ventilation garment (LCVG) simulator and water heater to simulate the metabolic output of a CM.[18]

The testing for the SWME was done on a comparative basis where there were two SERFEs. One of the units was tested on the ISS in microgravity, and the sister unit was tested on the ground. Each unit underwent a total of 25 simulated EVAs in series of four to five EVAs.[18] The SERFE units remained inactive for weeks between each series with a stagnant water loop and SWME fibers exposed to a pressurized and sealed chamber. It was important to test the SERFE in a comparative basis, because fluids behave differently in a microgravity environment than on earth.[18]

The success of the SERFE ultimately escalated the SWME to a TRL 8. Although the SWME was demonstrated on orbit in the flight experience SERFE, it has not reached TRL 9, as it has not been tested

in a completely integrated spacesuit in space. TRL 8 was achieved as it was tested through simulations on the ISS, and it achieved flight qualification.

V. Relevance

The spacesuit is a critical aspect of human spaceflight. For over 15 years, NASA has been designing, developing, and testing elements of the xEMU (shown in Figure 2) leading toward a Design, Verification, and Test (DVT) unit. The progression of acquired knowledge gained in the formulation of the xEMU DVT will be valuable for suit technology development and infusion for the future. The legacy knowledge gained from the Apollo and Shuttle/ISS EMUs (shown in Figure 1) will augment the xEMU knowledge to provide a rich foundation for industry involvement in human space exploration for the future. Now, that industry involvement has begun with spacesuits marking a new era in spacesuit development and technology infusion.

On April 29, 2021, the Biden-Harris administration showed strong support for NASA in the first 100 days of office. They expressed support for the Artemis Program and pledged to land the first woman and person of color on the surface of the moon under the Artemis Program.[19] On September 21, 2021, NASA published the plan to return to the moon in 2024 via the Artemis III mission. NASA noted that this mission would return humans to the surface of the moon wearing modern spacesuits that would allow for more flexibility and movement than those of their Apollo predecessors. This opportunity would last for seven days to collect samples and conduct science experiments.[20] On November 9, 2021, NASA Administrator Bill Nelson, via a media teleconference, relayed that the landing on the moon would be delayed to no earlier than 2025. There appeared to be several contributors to the delay, including insufficient appropriated dollars for the Human Landing System (HLS), litigation associated with HLS, and impacts caused by the pandemic.[21]

In September 2021, NASA released a solicitation for the Exploration Extravehicular Activity Services (xEVAS) to procure commercial services for advanced spacesuits with new capabilities for surface exploration, tools and equipment, vehicle interface and flight support hardware, along with EVA systems training and real-time operations support to NASA.[22] The plan would be to have over 60 unique EVAs with at least two CMs per EVA over the next decade, equating to over 120 EVAs. The xEVAS contract is planned as a services contract, not a contract where hardware is delivered. For spacesuits, the analogy is similar to renting a car. NASA would purchase the service of the spacesuit, not the spacesuit itself. However, NASA would certify the spacesuits for flight operations.[23]

On June 1, 2022, NASA announced the selection of Axiom Space and Collins Aerospace to provide services under the xEVAS contract. This award enables the vendors to compete for task orders during the period of performance through 2034. The xEVAS contract is an indefinite delivery and indefinite quantity, milestone-based contract with a potential value of \$3.5 billion. It will leverage government and/or commercial investments to provide an EVA system (space suit, associated hardware, and services) for a successful demonstration in a relevant environment and initial certification for first use by NASA CMs.[24]

On September 7, 2022, NASA announced the selection of Axiom Space as the awardee of the first task order issued under the new xEVAS contract. The task order is to develop the next generation Artemis spacesuit and

supporting systems, and to demonstrate the spacesuits use on the lunar surface during Artemis III. The xEVAS contract and the task order will be managed by the new NASA program, EVA and Human Surface Mobility Program (EHP) at the NASA JSC in Houston, Texas.[25]

Industry has now engaged through the xEVAS effort. Axiom Space now has the opportunity to be the first commercial entity to have their own spacesuit on the moon. As NASA defines the technical and safety standards by which the spacesuits will be built, it will share the development and ground-based test data from the ISS EMU and the xEMU.[24] The opportunity for technology infusion exists. It is desired that this research cannot only help spacesuit systems for the future, but other space systems as well.

VI. Advanced Technology and Infusion

Advancement in technology is paramount when looking to the future. NASA has invested in several advanced technologies as articulated in Section IV of this paper. NASA believes that the xEVAS effort will leverage the progression of technologies of the xEMU, along with the PLSS schematic study that was initiated in 2005. The technologies and architecture associated with xEMU have progressed in development over the last 17 years and can be shared with commercial partnerships for spacesuits.

This paper is an introduction to the spacesuit system architecture that has the potential to be used for the Artemis moonwalkers. The goal is to create a methodology to facilitate the optimization of spacesuit systems that will inspire new advanced technologies and pioneering exploration. The goal will be to benchmark off the analysis efforts that were first initiated by NASA in 2001 and updated to facilitate the schematic study performed between 2005 and 2007. The effort referenced is the Extravehicular Activity System Sizing Analysis Tool (EVAS_SAT).[26]

The purpose of the EVAS_SAT was to aid the conceptual design of an EVA system for the future. The EVAS_SAT was created to formulate an EVA system for future human exploration missions and to support spacesuit development efforts. The tool estimated the EVA system mass, volume, and power requirements for different EVA configurations and mission scenarios including spacesuit systems. The tool was intended to be used by the EVA community and was operated within Microsoft Excel 2003 using a Visual Basic interface system.[26]

The EVAS_SAT sizing approach used major subsystems such as the spacesuit, airlock, tools, and vehicle equipment and then separated those subsystems into technology-independent functional blocks that became inputs to the tool. Different technologies made up the functional blocks. Baseline sizing for existing and new technologies was determined.[26]

The EVAS_SAT tool influenced the schematic study years ago, which played a role in the formulation on the xEMU architecture as it exists today. However, the tool has not been used for over two decades and similar tools do not exist in the public domain. It is the aim of this research to learn from the success of the EVAS_SAT tool implementation, develop a new analysis capability, and potentially combine it with such approaches as Design Structure Matrix for infusing new and advanced technologies into spacesuit systems for the future. [27]

VII. Conclusion

This paper focuses on complicated systems that necessitate successful infusion of technologies. These systems include NASA's spacesuits used for EVA, including the Apollo EMU, the Shuttle/ISS EMU, and the xEMU architectures. Game changing life support technologies were discussed. An introduction to a methodology was discussed based on legacy tools such the EVAS_SAT combined with such tools as DSM to formulate a means to assess new technology opportunities as they are considered for infusion into new spacesuit configurations such as those that emerge from NASA's xEVAS contract. Future work includes building a new tool to incorporate key component parameters such as those considered in the EVAS_SAT tool. However, the parameters would be expanded to include for example TRL, life, and operability of the component. This research is in its infancy. However, with technology opportunities targeted for new capabilities for the lunar surface such as increased operability, sustainability, and longevity, a tool targeted to assess technology infusion into complicated systems would be of interest to industry and academic alike.

Acknowledgments

The primary author, C. Chullen, recognizes and thanks Dr. Claas Olthoff for his mentorship and Bruce Conger for his years of consultation regarding the PLSS advanced development.

References

- [1] Chullen, C., and Westheimer, D. T. Extravehicular Activity Technology Development Status and Forecast. 2011.
- [2] Thomas, K. S., and McMann, H. J. *U. S. Spacesuits*. Springer-Praxis, Chichester, UK, 2012.
- [3] Tzini, I. Dr. Buzz Aldrin. NASA. https://www.nasa.gov/content/national-space-council-users-advisory-group/membership_roster_b_aldrin/. Accessed Jun. 10, 2022.
- [4] Rurman, J. A. "HUMAN SPACE FLIGHT: A RECORD OF ACHIEVEMENT, 1961-1998." *MONOGRAPHS IN AEROSPACE HISTORY Number 9, August 1998*. 103–148, 360–365, 376. <https://www.hq.nasa.gov/office/pao/History/40thann/humanspf.htm>. Accessed Sep. 11, 2022.
- [5] Thomas, K. S., and McMann, H. J. *US Spacesuits*. Springer-Praxis, Chichester, UK, 2006.
- [6] Exploration Extravehicular Mobility Unit (XEMU) Infographic. https://www.nasa.gov/sites/default/files/thumbnails/image/xemu_infographic-02.jpg.
- [7] Chullen, C. Advanced Technology Infusion into a Spacesuit Portable Life Support System. 2022.
- [8] Johnson, B. J., and Buffington, J. A. EVA Systems Technology Gaps and Priorities 2017. 2017.
- [9] Chullen, C., Oliva, V., Andrews, G., Hargrove, S., and Rodgers, D. U.S. Spacesuit Knowledge Capture -- Creation, Curation, and Dissemination. 2022.
- [10] Schuller, M., Lalk, T., Klaus, D., Askew, R., Little, F., Godard, O., Wiseman, L., Abdelfattah, S., and Kobrick, R. *Portable Life Support Subsystem Schematic Study*. College Station, TX, 2005.
- [11] Ouellette, F. A., Winkler, H. E., and Smith, G. S. The Extended Duration Orbiter Regenerable CO₂ Removal System. 1990.
- [12] Fricker, J., Dryer, C., and Noffke, R. *Crew, Robotics, and Vehicle Equipment (CRAVE) Portable Life Support Subsystem Schematic Study Final Report*. Houston, TX, 2006.
- [13] Chullen, C., Campbell, C., Papale, W., Hawes, K., Wichowski, R., Locks, W., Suit, A. S., Systems, A. E., Unit, E. M., Engineer, P., Suit, S., Survival, C., Branch, S., Division, T. S., Suit, S., Survival, C., and Branch, S. "Rapid Cycle Amine 3.0 System Development." No. July, 2015, pp. 1–13.
- [14] Chullen, C., Campbell, C., Papale, W., Murray, S., Wichowski, R., Conger, B., and Mcmillin, S. Design and Development Comparison of Rapid Cycle Amine 1.0, 2.0, and 3.0. 2016.
- [15] Roberts, J. Spacesuit Evaporation Rejection Flight Experiment (SERFE). *Suit Up*. <https://www.nasa.gov/image-feature/spacesuit-evaporation-rejection-flight-experiment-serfe>. Accessed Sep. 13, 2022.
- [16] Gerstenmaier, W. *ISS EVA 23 Suit Water Intrusion Lessons Learned*. 2014.
- [17] Westheimer, D., Campbell, C., Contreras-Baker, A., and Steele, J. *SERFE Water Quality Results*.
- [18] Westheimer, D., Campbell, C., Greene, B., Contreras-Baker, A., Korona, F. A., and Everett, S. *SERFE Project Overview*. 2022.
- [19] Etkind, M., and McGuinness, J. "NASA Release 21-050, 'Biden-Harris Administration Shows Strong Support for NASA in First 100 Days.'" *NASA HQ News*, Apr 29, 2021.
- [20] Inclan, B., and Rydin, M. NASA Release 21-092, "NASA Publishes Artemis Plan to Land First Woman, Next Man on Moon in 2024." *Artemis*. <https://www.nasa.gov/press-release/nasa-publishes-artemis-plan-to-land-first-woman-next-man-on-moon-in-2024>. Accessed Sep. 11, 2022.
- [21] Foust, J. "NASA Delays Human Lunar Landing to at Least 2025." *SPACENEWS*. <https://spacenews.com/nasa-delays-human-lunar-landing-to-at-least-2025/>. Accessed Sep. 11, 2022.
- [22] NASA. Exploration Extravehicular Activity Services (XEVAS) Solicitation 80JSC21XEVAS. *SAM.GOV*. <https://sam.gov/opp/842f5330cf454559834b372155b6d421/view>. Accessed Jun. 1, 2022.
- [23] Kearney, L. Opening Plenary Session Speech. <https://www.ices.space/wp-content/uploads/2022/07/ICES-2022-Event-Program-St-Paul-MN-web-f-1.pdf>.
- [24] Lloyd, V., Hambleton, K., and Wickes, R. NASA Release 22-055, "NASA Partners with Industry for New Spacewalking, Moonwalking Services." *Humans in Space*. <https://www.nasa.gov/press-release/nasa-partners-with-industry-for-new-spacewalking-moonwalking-services>. Accessed Jun. 1, 2022.
- [25] Lloyd, V., Hambleton, K., and Wickes, R. NASA Release 22-093, "NASA Taps Axiom Space for First Artemis Moonwalking Spacesuits." *Humans in Space*. <https://www.nasa.gov/press-release/nasa-taps-axiom-space-for-first-artemis-moonwalking-spacesuits>. Accessed Sep. 7, 2022.
- [26] Brown, C., Conger, B., Miranda, B., Bue, G., and Rouen, M. Extravehicular Activity System Sizing Analysis Tool (EVAS_SAT) for Advanced Spacesuit Systems. 2007.
- [27] "The Designed Structure Matrix (DSM)." The Web-Portal of DSM Community. <http://www.dsmweb.org>. Accessed Sep. 14, 2022.