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Technology Infusion in U. S. Spacesuits – A Comparative System Analysis

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Abstract

The National Aeronautics and Space Administration (NASA) has evolved multiple spacesuit systems for performing extravehicular activity (EVA) or space walks. These spacesuit systems include the Apollo Extravehicular Mobility Unit (EMU), Space Shuttle and International Space Station (ISS) EMU, and Exploration EMU (xEMU). Each spacesuit system is like the other for functionality. However, each spacesuit system is different in configuration based on the technology infused into the system associated with the purpose of the mission. Each spacesuit system is made up of many components and the integrate environment targeted for operations leads to an integrated system that is complex. Since Apollo, NASA has invested in multiple technologies that make up these spacesuit systems in different iterations. The Apollo EMU was designed in the 1960's with a focus to facilitate the first human to walk on the moon. The Space Shuttle EMU was designed in the 1970's for reusable microgravity operations that began in the early 1980's. The Space Shuttle EMU was enhanced to facilitate extended operation on the ISS. Over the last 15 years, NASA has been designing, developing, and testing a new spacesuit system, the xEMU which is considered a design, verification, and test unit. NASA is planning to land the first woman and first person of color on the Moon. NASA recently engaged industry through a new contractual arrangement to provide EVA services needed to return to the Moon and to continue operations on the ISS. Spacesuit systems are complex. Understanding the requirements, operational environment, the necessary technologies, and the integrated spacesuit system are paramount. In addition, understanding the technology infusion process to meet the mission objectives is critical. This paper will review the spacesuit systems for EVA and several component functions within the spacesuits, along with a system comparison of those technologies from Apollo to xEMU.

Keywords: National Aeronautics and Space Administration; NASA; spacesuit; extravehicular activity; EVA; space walks; extravehicular mobility unit; EMU; Apollo; Space Shuttle; International Space Station; ISS

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Nomenclature

AES	Advanced Extravehicular Activity Suit
AS	Apollo-Saturn
CO_2	carbon dioxide
CCC	contaminant control cartridge
CM	crew member
DVT	design, verification, and test
EMU	Extravehicular Mobility Unit
EVA	extravehicular activity
Hrs	hours
ISS	International Space Station
JSC	Lyndon B. Johnson Space Center
LiOH	lithium hydroxide
LCG	Liquid Cooling Garment
lbs	pounds
MetOX	metal oxide
NASA	National Aeronautics and Space Administration
OPS	Oxygen Purge System
O_2	oxygen
PLSS	portable life support system
PSA	Pressure Suit Assembly
SSA	Space Suit Assembly
TCC	trace contaminant control
U.S.	United States

1. Introduction

The United States (U.S.) Extravehicular Activity (EVA) spacesuits are the most complex spacesuits ever conceived. What makes the EVA spacesuits complex is the requirement to operate in the environment of space outside the spacecraft. The space environment is unique, extreme, and harsh. An astronaut or crew member (CM) wearing an EVA spacesuit would be exposed to the vacuum of space, a varied array of temperature extremes and radiation, and contend with lunar dust on the Moon.[1] EVA spacesuits are like a spacecraft designed specifically to protect a CM while performing their duties outside a space vehicle. This paper focuses solely on the U.S. EVA spacesuits: the Apollo Extravehicular Mobility Unit (EMU); the Space Shuttle (referred to as Shuttle throughout this paper) and International Space Station (ISS) EMU; and the Exploration EMU (xEMU) design, verification, and test (DVT) unit. These U.S. EVA spacesuits are shown in Fig. 1.[2]

Technology infusion into complex systems can be evolutionary or revolutionary. Technology infused into U.S. spacesuits have been evolutionary.[3] For a technology to be successfully assimilated in an evolutionary way, a variety of interrelated factors must be present for the technology to reach its full potential. Examining the differences and similarities of the evolving technologies can help reduce the complexity of technology integration and develop better communication and cooperation between future technology developers and system integrators. As NASA sets its goals toward the Moon and Mars, a spacesuit design will be needed for these adverse environments and tolerable of gravity and dust. The xEMU as a DVT unit was built based on over 15 years of evolutionary technological progress and lessons learned and can serve as a foundation of knowledge for future spacesuits.[4] This paper compares specific technologies as they evolved from Apollo to xEMU.

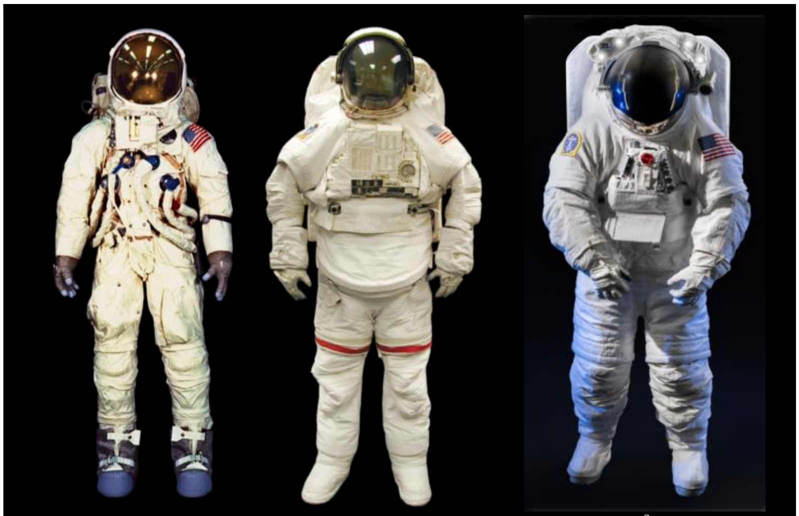

Fig. 1. Apollo EMU, Space Shuttle/ISS EMU, and xEMU[2]

2. Extravehicular Mobility Unit Systems

2.1. Apollo EMU

The Apollo Program established the groundwork for EVA spacesuits. The EVA spacesuits included a portable life support system (PLSS) for doing spacewalks. NASA structured three distinctive types of spacesuits for the Apollo Program. A block-based system was used to organize the spacesuits. Block I spacesuits were without EVA capability and were planned for the Apollo Command Module flights (1965-1967). In 1964, NASA decided to use a modified Gemini spacesuit design for the Block I Apollo spacecraft. On January 27, 1967 during the preflight test for Apollo-Saturn 204 (AS-204) mission, the tragic accident occurred on the launch pad at Cape Kennedy. Astronauts Virgil Grissom, Edward White and Roger Chaffee perished when a fire swept through the command module. Later that year, this mission would be officially named as Apollo 1.[5] The Block I spacesuit effort was terminated after the Apollo 1 mission pre-launch pad fire.[6] Neither Apollo 2 nor Apollo 3 were never designated as a mission or flight.[5] Apollo 4 was designated for the first Apollo-Saturn V mission (AS-501).[7] Apollo 4 (launched November 9, 1967) was the first-ever launch at NASA's Kennedy Space Center and was uncrewed.[8] Apollo 5 (AS-204) launched January 22, 1968 and Apollo 6 (AS-502) launched April 4, 1968 were uncrewed.[7]

The EVA spacesuit consisted of the Block II configuration and was used for the limited-duration lunar missions of Apollo 7 (AS-205) through 17 (AS-512) (1969-1972).[9] Apollo 17 was the final Apollo manned lunar landing mission.[10] Block III was dedicated to long-duration missions (35-day lunar visit capacity) and more sophisticated Advanced EVA Suit (AES) design. Block III flights were eventually cancelled before the culmination of the AES design.[9]

This paper focuses solely on the U.S. EVA spacesuits and referred to throughout this paper as EVA spacesuits. The EVA spacesuit was a crucial part of the Apollo missions. It allowed astronauts to explore the moon safely, and it was the first EVA spacesuit designed for use on the moon. The Apollo EMU development for Block II featured two distinct configurations. The first configuration was the EVA spacesuit system which included an A7L-type Pressure Suit Assembly (PSA), a PLSS, an Oxygen Purge System (OPS) (backup life support system), gloves, lunar boots, and a visor assembly. Additionally, this same modular suit system without the PLSS was the second configuration and was used as a launch and entry suit. The EVA spacesuit (Apollo 15-17) boasted a primary life support capability of 7 hours certified (longest use 7.62 hours) and a backup life support capability of 30 minutes certified, with an operating pressure of 3.7 psi (25.5 kPa).[9]

2.1.1. Apollo EMU PLSS

The Apollo EMU was developed in the 1960's. The Apollo EMU was like its own spaceship. It allowed the CM the ability to step foot on the moon and explore the lunar surface for the first time. During the Apollo program, the PLSS was the critical subsystem of the EMU that allowed CMs to do spacewalks independent of the Apollo Command Module. A photo of the Apollo EMU PLSS is shown in Fig. 2.[11] The Apollo EMU PLSS provided multiple functions to survive the CM. Specifically, it consisted of a primary life support system, emergency life support, communications, and telemetry during spacewalks. The Apollo PLSS critical life support functions that survived the crew member included the following: (a) pressure control, (b) breathing oxygen (O_2) supply, (c) ventilation, and (d) thermal control.[12] The ventilation system is a closed-loop gas system. This system provides humidity control, contaminant control, and thermal control.

Fig. 2. Apollo EMU PLSS[11]

2.1.2. Apollo EMU PLSS Schematic

The Apollo EMU PLSS subsystems included a primary O_2 subsystem, an O_2 ventilation circuit, a liquid transport loop, a feedwater loop, and an electrical power subsystem. The schematic of the Apollo 9 to 14 EMU PLSS which is a representation of these subsystems is shown in Fig. 3.[13]

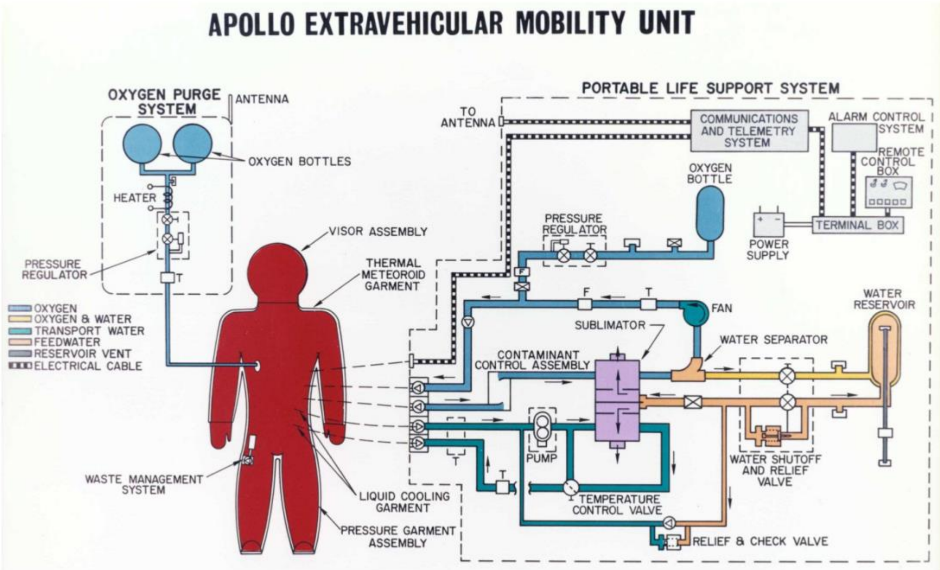

Fig. 3. Schematic of the Apollo 9 to 14 EMU PLSS[13]

The O_2 was stored in a pressurized bottle or tank. This tank provided the O_2 for CM breathing and for spacesuit pressurization. Before entering the O_2 ventilation circuit, the stored O_2 was regulated to the correct pressure. The O_2 ventilation circuit provided temperature, humidity, and contaminant control of breathing oxygen. A battery-powered fan circulated the O_2 gas into the spacesuit around the CM's head and body through the ventilation circuit. During lunar surface operations, all inlet O_2 flow was directed to the helmet for respiration and helmet defogging. After gas traveled through the body to the extremities, the return ducts directed the flow throughout the ventilation circuit where it picked up heat, moisture, and metabolic byproduct contaminants as it passed through the spacesuit adjacent to the CM’s body. The warm, moist gas and contaminant gases were transported to a contaminant control package. This consisted of an activated charcoal bed for absorption of trace contaminant gases, and a lithium hydroxide (LiOH) bed, which reacts with carbon dioxide (CO_2) to form lithium carbonate.[14]

The liquid transport loop was the key to keeping the CM comfortable. It circulated water from the liquid cooling garment (LCG) through the sublimator (heat exchanger), which removed heat, before cooling the fan motor and returning to the LCG. To ensure the sublimator could cool down the water, a feedwater loop provided extra water and stored condensation that was taken from the oxygen ventilation circuit by the water separator. Meanwhile, the electrical power subsystem supplied electricity to the fan and pump motor assemblies, communication systems and instrumentation, and the Extravehicular Communications System enabled voice communication and system performance telemetry transmission.[15]

2.2. Shuttle/International Space Station “Enhanced” EMU

The focus for the Shuttle EMU was to be a reusable spacesuit. The desire was for the Shuttle EMU to be robust, compact, maintainable, and universally sizable. About the same time as the later Apollo missions were cancelled, the Shuttle was only a concept. However, development of the Shuttle EMU would be greatly influenced by the advanced development of the Apollo EVA spacesuits. Initially, spacewalks envisioned for the Shuttle were concepted for emergency use only.[9] Fortunately, the Shuttle EMU went on to become the baseline EMU for decades.

By 1974, NASA was well on its way to procure a new Shuttle EMU. For the Shuttle EMU, it would be volume, weight, and budget constraints that would influence the Shuttle design. One of the more significant design requirements to minimize development risk was the minimum operating pressure of 4.0 psi (27.6 kPa). The goal was to reduce the amount of time necessary to rebreathe before doing an EVA. A review of the PLSS design allowed the operating pressure to be increased to 4.3 psi (30 kPa). This also allowed for no redesign of major components. The Apollo EMU operating pressure was 3.7 psi (25.5 kPa). Another significant requirement would be size. The baseline Shuttle EMU ended up being somewhat heavier at the 4.3 psi (30 kPa) design than the original design at the 4.0 psi (27.6 kPa) design. The baseline ended up weighing 375 lbs (170 Kg) versus 312 lbs (141.5 kg) for the original design. It would need to accommodate 5th percentile female to a 95th percentile male. Also, the Shuttle EMU would need to have a 6-year useful life on pressure suit elements. In addition, it would need to have a 15-year life on the life support systems. The operating capacity would need to be 7 hours with a 30-minute emergency back-up system.[9] By 1977, NASA had selected a design for the new Shuttle EMU. The first EVA on the Shuttle would take place in 1983.[9] The baseline design would represent configurations of the Shuttle EMU that existed before 1990. Thereafter, incremental improvements or enhancements would be made to target the design toward the Space Station Freedom (now ISS). Thereafter, the EMU for ISS would be known as the "Enhanced" EMU.

The enhanced EMU or as in this paper referred to as the ISS EMU has culminated over 30 years of active operation from 1990 to present. The ISS EMU remains in operation today on the ISS. The enhancements were evolutionary in nature over the years from the Shuttle EMU to the ISS EMU. Nearly every subassembly of the EMU was revised or improved. Enhancements included converting to a contract end item approach with more modularity. Other improvements included an optional propulsion module for self-return of a CM who may become detached from the vehicle. Additionally, improvements included the ability to change out modules of the spacesuit on orbit, improved thermal control, and improved lights and camera systems. The first improved item flew in 1994. However, in 1998, NASA debut the fully enhanced or ISS EMU. In 2004, NASA merged all operations of the EMU under one contract simplifying the organizational structure. The operating pressure was 4.3 psi (29.6 kPa). The total weight on earth was 275 lbs (124.7 kg). The operation capacity was 8 hours nominally with the longest used at 8.93 hours. The emergency backup oxygen system was certified at 30 minutes.[16]

The Shuttle and ISS EMU together has culminated in almost 40 years of spacewalks since inception. The EMU has facilitated inspections of the Shuttle and many repairs including the Hubble Space Telescope. The construction of the ISS would not have been possible without the EMU. Even satellites have been retrieved by CMs in the EMU. With so many accomplishments, the EMU has become the true workhorse of EVAs for NASA.[16]

2.2.1. Shuttle/ISS EMU PLSS

The Shuttle/ISS EMU consists of two main subsystems: the Space Suit Assembly (SSA) and the PLSS. It was built to provide environmental protection, mobility, life support, and communication abilities to the CMs during EVAs or spacewalks. The ISS EMU is currently the only pressurized flight suit in the United States that allows for a CM to perform spacewalks in zero gravity. Although the Shuttle/ISS 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.[16]

The Shuttle/ISS EMU PLSS consists of a Primary Life Support System and a Secondary Oxygen Supply as shown in Fig. 4.[17] The PLSS is made up of the four major circuits.[16] The circuits include Oxygen Ventilation Circuit, the Primary Oxygen Circuit, the Feedwater Circuit, and the Liquid Transport Circuit.

The Shuttle/ISS EMU's PLSS will form the benchmark for life support technology architectures for lunar and Martian surfaces. Just as the Shuttle/ISS EMU drew inspiration from the Apollo EMU, the reverse will occur as the future spacesuits will draw 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.

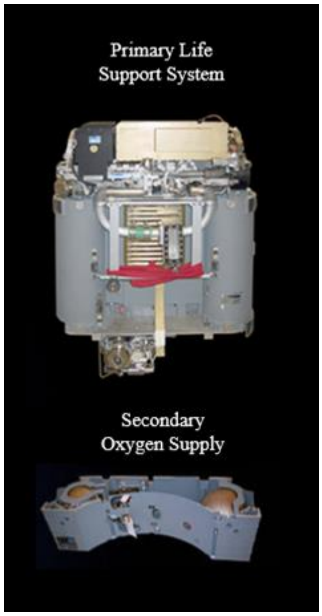

Fig. 4. Shuttle/ISS EMU PLSS Primary Life Support System (top) and Secondary Oxygen Supply (bottom)[17]

2.2.2. Space Shuttle/ISS EMU PLSS Schematic

The Space Shuttle/ISS EMU was developed in the 1970's. The schematic of the Space Shuttle/ISS EMU PLSS is in Fig. 5.[16] The PLSS provides life support for the CM. The PLSS provides breathing oxygen and controls the pressure of the CM's spacesuit. It provides thermal control, removes humidity, odors, carbon dioxide, and other contaminants. The Shuttle/ISS EMU uses a single gas pure oxygen supply with a primary and secondary loop. Metabolic waste heat is removed from the CM using liquid water flowing through a liquid cooling and ventilation garment (similar to the LCG in the Apollo EMU PLSS) in the thermal loop. A pump is used to move the thermal loop. A single fan is used to circulate the oxygen through the ventilation loop. The entire PLSS is packaged into a backpack attached to the SSA. In the ventilation, the Shuttle/ISS EMU PLSS coupled a fan, water pump, and rotary pitot water separator that became known as the Fan/Pump/Separator. This ultimately saved power over the Apollo EMU PLSS design. In the Shuttle/ISS EMU PLSS, the CO_2 was removed in the ventilation loop. The CO_2 removal and trace contaminant control (TCC) are also accomplished in the ventilation loop and is discussed in Section 3 of this paper.[3]

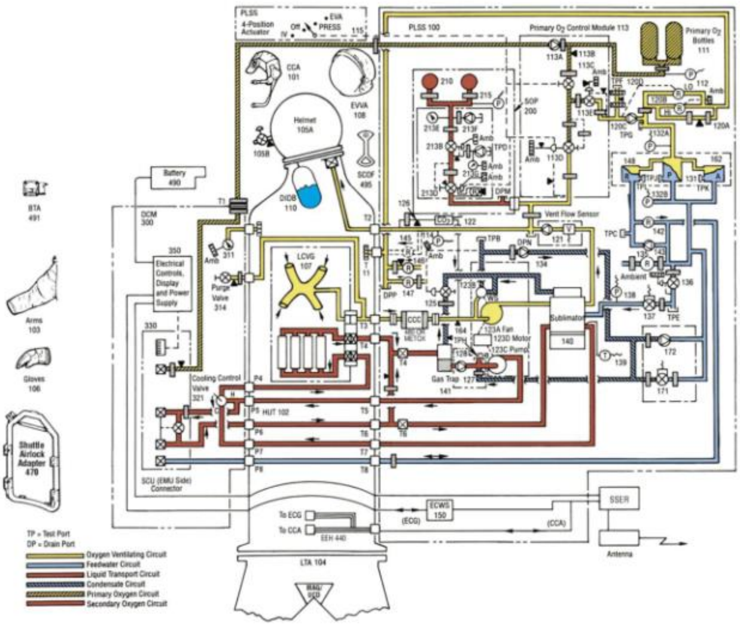

Fig. 5. Schematic of the Shuttle/ISS EMU PLSS[16]

2.1. Exploration EMU

The first new spacesuit design and assemble in 40 years is known as the xEMU as shown in Fig. 1.[2] For the last 15 years, NASA has been designing, developing, testing, and evaluating the xEMU in house at the at the Lyndon B. Johnson Space Center (JSC) in Houston, Texas. The xEMU was designed with increased performance capabilities as the goal. The focus was to create a robust, safe, and reliable spacesuit for a long-duration lunar application. The xEMU incorporates a culmination of lessons learned from NASA's historical spacesuits. It also includes innovations and several new technologies. The xEMU is different from the Apollo and Shuttle/ISS EMUs. The unique features include being a rear entry spacesuit that targets more mobility and flexibility of movement. It also marks new era in technology advancements as well as lessons learned from the past. The xEMU DVT unit consists of two main subsystems including the Pressure Garment System and the PLSS. Fig. 6 identifies several innovations in the xEMU.[18] Several innovations include high speed data communication, high definition video and lights, informatics display and control, integrated communications, automated suit check out, enhanced upper mobility, Environmental Protection Garment with dust mitigation, 4.3 to 8.2 psi variable pressure, one-hour emergency return, vacuum regenerable CO_2 removal system, membrane evaporation cooling, modular PLSS design, and rear entry ingress and egress. The xEMU is consists of over 90 individual components. The xEMU design will facilitate the first woman and the next man to walk on the moon. This next generation spacesuit has incorporated many new technologies and capabilities to enable EVAs in deep space, lunar EVAs, and will formulate the foundation for exploration on Mars.

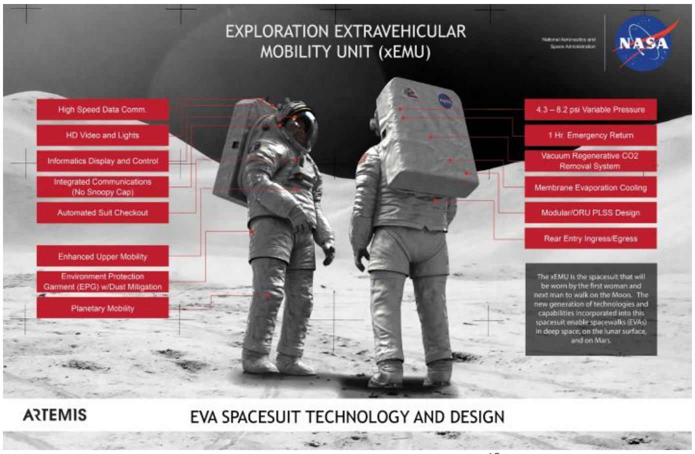

Fig. 6. Exploration EMU (xEMU)[18]

2.1.1. Exploration EMU PLSS

The xEMU PLSS incorporates many new technologies. These technologies were selected based on the results of the schematic study in 2005.[19] The technologies were funded by various programs which facilitated them into over 15 years of development resulting into an integrated DVT PLSS design. In addition, the technology infusion into the xEMU was not only based on the schematic study, but it was also formulated from the many lessons learned taken from the Shuttle/ISS EMU PLSS operations. This knowledge was obtained from failures and successes of the spacesuit system used to support the Shuttle and the ISS for over 40 years. The xEMU PLSS (Fig. 7[20]) forms the critical function that enables autonomous operation independent of the space vehicle.[3]

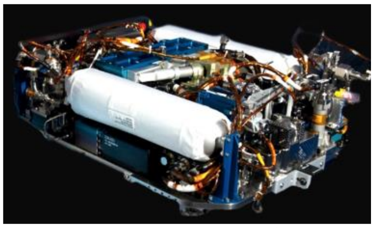

Fig. 7. xEMU PLSS[20]

2.1.2. Exploration EMU Schematic

The xEMU resulted of technology development along with the lessons learned of the past. However, it was a PLSS schematic study that influenced the design of the xEMU and facilitated the infusion path for game-changing

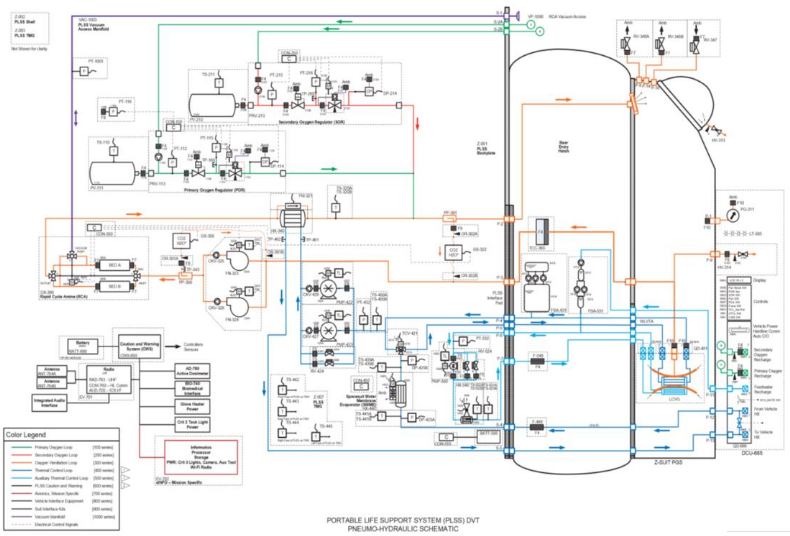

Fig. 8 Exploration EMU PLSS Schematic[21]

technologies.[19] NASA engineers thoroughly evaluated the PLSS schematic options along with technology options. A team of experts review the results which culminated in a down select of the technologies. Once the schematic was selected, nearly 15 years of continued development, design, testing, and evaluation would result in the xEMU schematic. The schematic of the xEMU PLSS is in Fig. 8.[21] The xEMU was designed with a primary O_2 loop, a secondary O_2 loop, an O_2 ventilation loop, a thermal control loop, an auxiliary thermal control loop, and vacuum access manifolds.

3. A Comparative System Analysis

The EMU was developed during the Apollo program. The Shuttle and ISS Programs facilitated additional technology maturation of the EMU. And more recently, the xEMU took a thorough approach for advancing the spacesuit with new technologies. It culminated decades of lessons learned along with a far-reaching PLSS schematic study to search for technology that could potentially meet the requirements.[19] The entire spacesuit system is extremely complicated due to the environment and conditions that it has to operate in. The most significant aspect of the EMU is that it allows a CM to leave the vehicle in the vacuum of space and operate like its own spaceship. This excursion is the ultimate fieldtrip known as an EVA. An EVA can be accomplished by an umbilical where the life support is connected back to the vehicle. However, to accomplish an EVA without an umbilical, an EMU PLSS is required for that spacesuit system. Therefore, the EMU PLSS is the focus of this paper due to its uniqueness and the freedom it awards a CM. An EMU PLSS has enabled walking on the Moon during Apollo, inspecting critical components outside

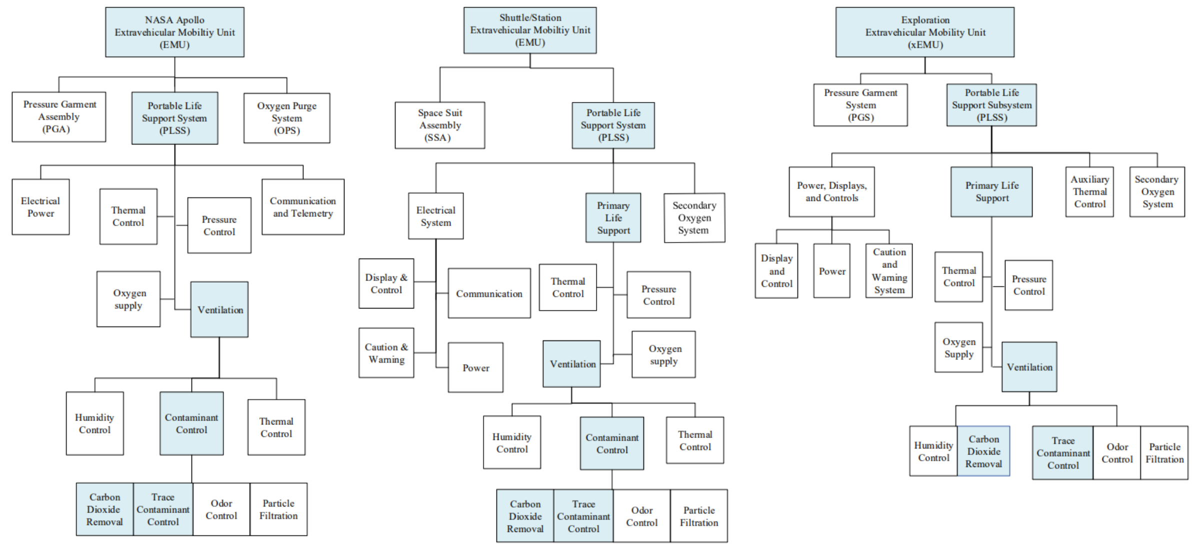

Fig. 9. Partial hierarchies for Apollo EMU PLSS (left), Shuttle/ISS EMU PLSS (middle), and the xEMU PLSS (right)

the Shuttle, building the ISS, capturing satellites, repairing the Hubble Space Telescope, and performing many other critical jobs during the history of human space flight.[22]

The PLSS schematic study fostered the infusion path for new technologies into the xEMU PLSS. Many years of technology development took place to reach a point where the technologies from the study were integrated into xEMU PLSS. Although it was difficult to align the xEMU design toward multiple architectures, technical priorities, and design reference missions, the technology progression was monumental. To appreciate the significance of the technology infusion achievements of the xEMU PLSS, it is important to understand the functionality of all three EMU designs including Apollo EMU PLSS, Shuttle/ISS EMU PLSS, and the xEMU PLSS. To accomplish this understanding of functionality, a comparative system analysis is used. Partial functional hierarchies for Apollo EMU PLSS, Shuttle/ISS EMU PLSS, and the xEMU PLSS is shown in Fig. 9. The functions of CO_2 removal, contaminant control, and humidity control has been chosen as the example functions to compare between the Apollo EMU PLSS, Shuttle/ISS EMU PLSS, and the xEMU PLSS.

The PLSS subsystem in all three spacesuit systems is divided into several groupings, circuits or loops as shown in Fig. 9. In the Apollo EMU hierarchy (left), the PLSS is divided into subsidiary functions: thermal control, pressure control, O_2 supply, and ventilation as well as electrical power and communications and telemetry. The Shuttle/ISS EMU PLSS (middle) is also divided into subsidiary functions somewhat differently. The functions are more tiered. As such, the PLSS is broken down into the primary life support, secondary O_2 system, and the electrical system. The primary life support system consists of the thermal control, pressure control, O_2 supply, and ventilation. Similarly, in the xEMU hierarchy (right), the PLSS consists of the primary life support and secondary O_2 system. However, the xEMU PLSS also includes a subsidiary function of auxiliary thermal control. In addition, the power is configured somewhat different as it is included in the power, displays, and controls function. The primary life support system in the xEMU consists of the thermal control, pressure control, O_2 supply, and ventilation. The ventilation function is consistent within all three suit configurations. The technologies addressed in this paper focus on how the humidity control, contaminant control, CO_2 removal, and TCC are achieved.

The life support functions of a spacesuit are critical for survival in space. The spacesuit provides the suited CM with a source of oxygen, and it also removes CO_2 from their exhaled breath. The spacesuit also regulates the CM's temperature, to protect them from extreme temperatures and to ensure that the spacesuit does not become overburdened with heat.[23] The CO_2 levels on Earth are managed by respiration and the environment. The O_2 is inhaled and is transported via the bloodstream to the lungs where the conversion to CO_2 occurs. When the body functions nominally, CO_2 is eliminated through exhalation. An inability to adequately regulate CO_2 levels can result in hypercapnia and can lead to symptoms such as headache, dyspnea, and fatigue, or in extreme cases, death. Natural removal of CO_2 is achieved through processes such as photosynthesis, weathering, and other experimental CO_2 removal processes. However, these processes are not available in enclosed environments, such as vehicles and spacesuits. Therefore, different approaches are necessary to facilitate CO_2 removal within a spacesuit. Specifically, the component(s) used to accomplish both the CO_2 removal, humidity control, and TCC are compared and contrasted from a pictorial, descriptive, and parametric standpoint.

In the Apollo EMU PLSS, the function of contaminant control includes CO_2 removal, TCC, and particle filtration. The CO_2 removal was accomplished by a LiOH cartridge. Due to its ability to absorb CO_2 and become lithium carbonate, using LiOH to remove CO_2 was favored by space programs since the beginning of manned space flight. However, it was not regenerable. Once it reached its capacity to remove CO_2, it would have to be discarded and replaced which contributes to increased logistics. Apollo EMU PLSS used the term contaminant control cartridge (CCC) as it not only used LiOH for CO_2 removal, but it also contained particulate and charcoal odor filters.[9]

In the Shuttle/ISS EMU PLSS, the CO_2 removal, TCC, and particle filtration are performed by the CCC as well. However, there are two versions of the CCC that exist. The two versions include the LiOH CCC (Fig. 10[24]) and the metal oxide (MetOx) CCC (Fig.11).[2225] The two versions are interchangeable in the ISS EMU PLSS. The LiOH CCC was used for both Shuttle and ISS. However, the MetOx CCC was solely used for ISS EMU PLSS. The MetOx CCC can be regenerated on-orbit and on earth for reuse. The LiOH CCC contains a LiOH bed for CO_2 removal, an activated charcoal bed for trace contaminant removal, and a particulate filter to trap particles and prevent migration of LiOH dust. The MetOx CCC uses metal oxide as the CO_2 sorbent material, activated charcoal for trace contaminant removal, and a filter is at the outlet header to serve as particulate filter. The LiOH CCC can only be used once. The MetOx CCC can be removed, regenerated, and replaced. The MetOx CCC development was initiated in 1996 to overt the logistical challenges with replacing the LiOH CCC after each use.[16]

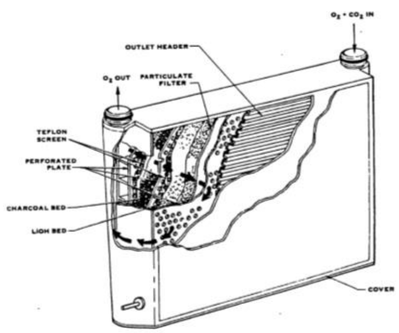

Fig.10. Contaminant Control Cartridge[24]

In the xEMU, the CO_2 removal is accomplished by the innovative Rapid Cycle Amine (RCA) swing bed technology. The RCA is a new technology and has never been used in other spacesuits. It is a vacuum-regenerable technology that has the capability to remove CO_2 and humidity. This particular technology simplifies the PLSS schematic by eliminating the need for a condensing heat exchanger for humidity control. Several RCA prototypes have been designed, fabricated, and tested a JSC. The RCA is designed with two alternating solid-amine beds to remove CO_2 and humidity (adsorb) in one bed and regenerate the solid-amine at vacuum (desorb) in the other bed.

The solid amine contained in the RCA that is capable of removing CO_2 and humidity is a formerly patented chemical known as TEPAN. TEPAN is the referred to as the term used for the solid amine that combines the reaction of tetraethylenepentamine (TEPA) and acrylonitrile (AN). A picture of the early prototype design of the RCA 1.0 sits beside a MetOX cannister shown in Fig. 11.[22] The RCA 3.0 design is shown in Fig. 12.[25] The development of RCA 3.0 was pursued after successful testing of RCA 1.0 and 2.0 at JSC. The RCA 3.0 unit was designed, fabricated, assembled, and performance tested in 2014.[25]

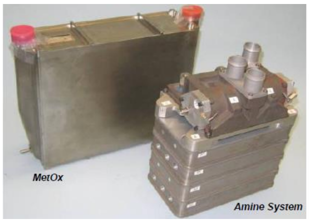

Fig. 11. RCA 1.0 with a MetOx Unit[22]

In the xEMU, TCC is accomplished as a separate component. A chemical known as Ammonasorb II is a commercial sorbent. It is a phosphoric acid impregnated activated carbon. This chemical is favored due to its ability to remove ammonia which is a byproduct of the RCA. The TCC design can be seen in Fig. 13.[26]

The CO_2 removal and TCC is changed significantly since Apollo EMU PLSS was designed and operated. Improvements were made for ISS to achieve less logistics with change out of the LiOH after each flight. MetOX was implemented and still used today for EVA on orbit at the ISS. However, the most significant change was the move to completely regenerable RCA technology to eliminate the need for change out. Table 1 compares the different technologies used for CO_2 removal and TCC.

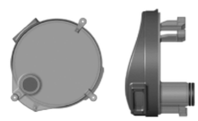

Fig. 13. TCC Design Top & Bottom[26]

Fig. 12. RCA 3.0 Unit[25]

Table 1. EMUs (Apollo/Shuttle/ISS/xEMU) compared for CO_2 control and TCC

	Apollo EMU	Shuttle/ISS EMU	Exploration EMU

EVA	• 3.7 psi (25.5 kPa)
	• 7 hrs certified
	• 7.62 hrs longest use
		• 4.3 psi (29.6 kPa)
		• Baseline for Shuttle:
		  o 8 hrs nominal
		  o 8.48 hrs longest use
		• Enhanced EMU
		  o 8 hrs nominal
		  o 8.93 hrs longest use
			• Not Flight Certified
			• Current Configuration: Design, Verification, & Test (DVT)

CO_2 Control	• CCC
	  o LiOH (Non-regenerable)
	    ▪ ~2 lbs CO_2 removal capacity
	    ▪ LiOH cannister needs repacking on ground after each use
	    ▪ Byproduct of LiOH is heat & moisture
	    ▪ Integrated into CCC with activated charcoal
		• CCC
		  o LiOH (Non-regenerable)
		    ▪ ~2 lbs CO_2 removal capacity
		    ▪ LiOH cannister needs repacking on ground after each use
		  o MetOx (Regenerable alternate to LiOH)
		    ▪ ~1.6 lbs CO2 removal capacity
		    ▪ MetOx cannister interchangeable with LiOH cannister
		    ▪ Regenerative after each EVA: 10 hrs at 400 °F + 4 hrs cool down = 14 hrs total)
		    ▪ Regenerated external to EMU on orbit or on ground
		  o Both LiOH & MetOx integrated into CCC with activated charcoal
			• Rapid Cycling Amine (RCA)
			  o TEPAN
			  o Regenerates during EVA
			  o Dual bed design allows for transfer of heat back and forth (No cooling required)
			  o No recharging or replacement after EVA
			  o Vents CO_2 & Humidity to vacuum
			  o Requirement: 100 EVAs @ 8 hrs each

Trace Contaminant Control	• CCC
	  o Activated Charcoal
	    ▪ Integrated into CCC with LiOH
		• CCC
		  o Activated Charcoal
		    ▪ Integrated into CCC with LiOH
			• TCC
			  o Ammonasorb II (Phosphoric acid impregnated activated carbon)
			  o Separate Component from RCA
			  o Requirement: Minimum of 150 hours EVA time

4. Conclusion

This paper focuses on NASA's spacesuits used for EVA that have evolved over time through Apollo, Shuttle, ISS, and Exploration architectures. The schematics of each PLSS is revealed. A schematic hierarchy is shared of how the PLSS is grouped into circuits or loops and then broken down at the component level. The PLSS is a complicated system, and this paper provides the insight into the details of the PLSS from a comparison perspective. The technologies are itemized in each of the hierarchies. A comparison will be discussed. Future work includes building a new tool to incorporate key component parameters such as those considered in this paper. 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.

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