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NASA's Management and Development of Spacesuits

April 26, 2017

Report No. IG-17-018

Office of Inspector General

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RESULTS IN BRIEF

NASA's Management and Development of Spacesuits

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April 26, 2017 IG-17-018 (A-16-014-00)

WHY WE PERFORMED THIS AUDIT

Beginning with the Gemini 4 mission in June 1965, NASA astronauts have ventured outside their spacecraft hundreds of times wearing specialized suits that protect them from the harsh environments of space and provide the oxygen and temperature control necessary to preserve life. The spacesuits NASA astronauts currently use on the International Space Station (ISS or Station) – known as Extravehicular Mobility Units (EMU) – were developed more than 40 years ago and have far outlasted their original 15-year design life.

While maintaining the existing fleet of EMUs for use on the ISS, the Agency has also spent almost $200 million on three spacesuit development efforts to enable human exploration in deep space, including missions to Mars: the Constellation Space Suit System ($135.6 million), Advanced Space Suit Project ($51.6 million), and Orion Crew Survival System ($12 million). A key part of these development efforts will be testing the next-generation spacesuit technologies on the ISS prior to its scheduled retirement in 2024.

In this audit, we examined NASA's efforts to maintain its existing spacesuits and its plans for and progress in developing its next-generation spacesuits. To complete this work, we interviewed Agency and other relevant officials; analyzed cost, schedule, and performance data; and reviewed relevant reports, documents, and presentations.

WHAT WE FOUND

NASA continues to manage an array of design and health risks associated with the EMUs used by ISS crew. In addition, only 11 of the 18 original EMU Primary Life Support System units – a backpack-like structure that performs a variety of functions required to keep an astronaut alive during a spacewalk – are still in use, raising concerns that the inventory may not be adequate to last through the planned retirement of the ISS. Given these issues, NASA will be challenged to continue to support ISS needs with the current fleet of EMUs through 2024, a challenge that will escalate significantly if Station operations are extended to 2028.

Despite spending nearly $200 million on NASA's next-generation spacesuit technologies, the Agency remains years away from having a flight-ready spacesuit capable of replacing the EMU or suitable for use on future exploration missions. As different missions require different designs, the lack of a formal plan and specific destinations for future missions has complicated spacesuit development. Moreover, the Agency has reduced the funding dedicated to spacesuit development in favor of other priorities such as an in-space habitat.

After examining these spacesuit development efforts, we question NASA's decision to continue funding a contract associated with the Constellation Program after cancellation of that Program and a recommendation made by Johnson Space Center officials in 2011 to cancel the contract. Rather than terminate the contract, NASA paid the contractor $80.8 million between 2011 and 2016 for spacesuit technology development, despite parallel development activities being conducted within NASA's Advanced Exploration Systems Division. Moreover, given the current development schedule, a significant risk exists that a next-generation spacesuit prototype will not be sufficiently mature in time to test it on the ISS prior to 2024. Finally, little schedule margin exists between anticipated delivery of the Orion Crew Survival System spacesuit in March 2021 and NASA's current internal launch date of August 2021 for its first crewed mission beyond low Earth orbit.

What We Recommended

To maintain the efficacy of the current EMUs and ensure successful development of a next-generation spacesuit, we recommended the Associate Administrator for the Human Exploration and Operations Mission Directorate (1) develop and implement a formal plan for design, production, and testing of the next-generation extravehicular activity (EVA) spacesuits in accordance with the exploration goals of the Agency, crew needs, and the planned retirement of the ISS in 2024; (2) conduct a trade study comparing the cost of maintaining the current EMU spacesuit and developing and testing a next-generation spacesuit; and (3) apply lessons learned from operations of existing EVA and launch, entry, and abort spacesuit systems to the design of future exploration spacesuit systems to ensure mitigation of non-life-threatening health risks or other injuries that could impair mission objectives.

In response to a draft of this report, NASA management concurred with our recommendations and described its corrective actions. We consider management's comments responsive; therefore, the recommendations are resolved and will be closed upon verification and completion of the proposed corrective actions.

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TABLE OF CONTENTS

Acronyms

ACES	Advanced Crew Escape System
AES	Advanced Exploration Systems
CSSS	Constellation Space Suit System
EMU	Extravehicular Mobility Unit
EVA	Extravehicular Activity
FY	Fiscal Year
ISS	International Space Station
mEMU	Mars Extravehicular Mobility Unit
OCSS	Orion Crew Survival System
OIG	Office of Inspector General
PGS	Pressure Garment System
PLSS	Primary Life Support System
xEMU	Exploration Extravehicular Mobility Unit

INTRODUCTION

Beginning with the Gemini 4 mission in June 1965, NASA astronauts have ventured outside their spacecraft hundreds of times wearing specialized spacesuits that protect them from the harsh environments of space and provide the oxygen and temperature control necessary to preserve life. Since that time, suited astronauts have conducted 18 moonwalks, serviced the Hubble Space Telescope 23 times in low Earth orbit, and ventured outside the Space Shuttle (Shuttle) and the International Space Station (ISS or Station) 82 times and 122 times, respectively. However, the spacesuits NASA astronauts currently use on spacewalks from the ISS were developed more than 40 years ago and have far outlasted their original 15-year design life.

At the same time it maintains the existing fleet of spacesuits for use on the ISS, NASA is developing next-generation spacesuits to enable human exploration in deep space, including missions to Mars. A key part of this effort will be testing these spacesuits on the ISS, which, under the Agency's current plans, is scheduled to retire in 2024.

In this audit, we examined NASA's efforts to maintain its existing spacesuits and the Agency's plans for and progress in developing its next-generation spacesuits. Details of the audit's scope and methodology are outlined in Appendix A.

Background

Spacesuits are essentially personal spacecraft that provide all the functions necessary to support humans in space. First utilized in 1961 during the Mercury Program, spacesuits have evolved as NASA missions have progressed from working inside the pressurized environment of a spacecraft, to exploring the Moon, to working outside the Space Shuttle and ISS.[1] As the Agency prepares to send humans deeper into space, NASA has efforts underway to develop a spacesuit suitable for the gravity, planetary composition, radiation, and atmosphere of new environments.

Current Spacesuit Design

Developed beginning in 1974 and first flown in 1981, Extravehicular Mobility Units (EMU) are the only spacesuits NASA currently uses for spacewalks or "extravehicular activities" (EVA). Designed for the Space Shuttle Program, each EMU has been partially redesigned and completely refurbished multiple times over the last 40 years. For example, in the 1990s NASA added glove heaters and an emergency rescue propulsion module and improved the EMUs' lights and cameras. The ISS Program plans to use the EMUs through retirement of the Station.[2]

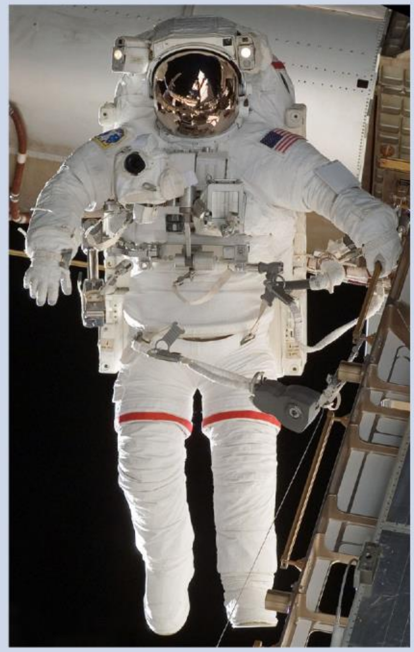
1 For more on the history of spacesuits and NASA's extravehicular activities, see Appendix B.

2 NASA is assessing the feasibility of extending ISS operations to 2028. Although NASA is considering using the existing spacesuits for ISS EVAs until then, it has also begun to develop next-generation spacesuit technologies that could be tested on the ISS by 2023 and potentially replace the EMUs.

The EMU is designed to sustain life outside the Station or another space vehicle traveling in low Earth orbit by providing air, water, and pressurization. The outer portion of the EMU contains two major subsystems: the Pressure Garment System (PGS) and the Primary Life Support System (PLSS).

The primary purpose of the PGS is to maintain appropriate pressure around astronauts' bodies to keep them alive in the vacuum of space while also providing sufficient mobility for operations.[3] The PGS is covered by a thermal micrometeoroid material that insulates the astronaut, prevents heat loss, and protects the astronaut from micrometeoroids and other orbital debris that could puncture and depressurize the suit. The PGS also features components known as "soft goods" – the arms, legs, gloves, waist, and boots – and "hard goods" – the Hard Upper Torso, helmet, and joint bearings. Underneath the PGS, astronauts wear liquid cooling and ventilation garments through which cool water flows to help regulate body temperature.

EMU Suit in Use Outside the ISS



Source: NASA.

The PLSS is a backpack-like structure with components that perform a variety of functions required to keep an astronaut alive during an EVA, including maintaining body temperature, providing oxygen for up to 7 hours, and removing carbon dioxide and humidity that build up inside the suit. Of the original 18 EMU PLSS units produced, only 11 remain available for use.

Oxygen from the PLSS enters the suit at the helmet and flows from behind the astronaut's head down through the suit. Oxygen and carbon dioxide are then returned from the PGS to the PLSS via ports near the astronaut's arms and legs. The gas removed from the suit is filtered through a cartridge that consists of an activated charcoal bed and either lithium hydroxide or metal oxide to remove carbon dioxide, odors, and dust. The oxygen then goes through a fan and is routed through a sublimator, where it is cooled to 57 degrees Fahrenheit.[4] Water that condenses in the sublimator, as well as gas, is sent to a water separator, which has an input from the gas trap in the cooling loop. The water is returned to the cooling loop or "feedwater" tanks and the gas to the ventilation loop. After passing through the sublimator, the gas flow goes through a flow rate sensor and back to the PGS.

The EMU is equipped with a water cooling system that takes warm water from the cooling garment and divides it into two loops. One loop goes to the sublimator, where the water is cooled and sent back to the cooling control valve. The other loop goes directly back to the control valve where the loops are recombined to allow full flow of water to be pumped back to the cooling garment. This process allows the garment to maintain a constant flow of cooling water, the temperature of which the astronaut can

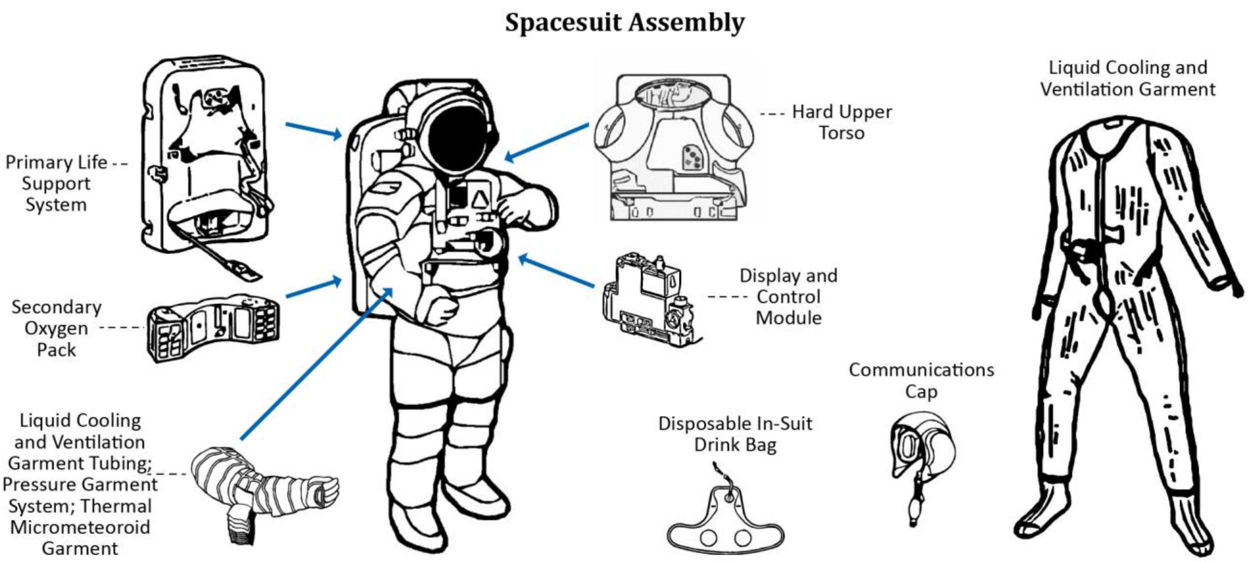
[3] To function normally, a healthy human body requires approximately 3 pounds per square inch of oxygen pressure in the lungs, the amount available at sea level on Earth.

[4] The sublimator works on the principle of sublimation, or the process by which a solid turns directly into a vapor, bypassing the liquid phase. In this case, ice is formed on the sublimator evaporator sieve and is allowed to vaporize into space, thereby removing excess heat.

control using the valve. During the process, the water from the cooling garment passes through a gas separator that ensures the cooling loop is free from gas bubble intrusion, which could render the water pump inoperable. In the event of PLSS failure, astronauts maintain 30 minutes of oxygen in a secondary oxygen pack located beneath the PLSS on the astronaut's back. The PGS and PLSS are connected by the Hard Upper Torso – a fiberglass shell with metal attachment bearings at the neck, arms, and lower torso for attaching the helmet, other PGS components, and a chest-mounted display and control module. This module contains all the switches, gauges, valves, and displays necessary to operate the PLSS.

Inside the spacesuit, astronauts wear a disposable drink bag, waste collection garment, communications cap, helmet absorption pad, liquid cooling and ventilation garment, and snorkel.[5] These items enable astronauts to perform their tasks while staying hydrated, eliminating waste, remaining cool, and receiving instruction from ground control or other crewmembers. The helmet absorption pad and snorkel were added in 2013 and provide for water absorption and alternative air sources in the event of water leakage into the EMU helmet. Figure 1 shows how the components of the EMU fit together.

Figure 1: Spacesuit Components



Source: NASA.

[5] The helmet absorption pad is a spongy material that can absorb up to 800 milliliters of liquid, while the snorkel allows astronauts to access air circulating in the lower portion of the EMU.

Spacesuit Certification

To address the risks associated with the EMU, including age-related failures and technical issues, NASA created the Assured EMU Availability Plan (Availability Plan) and the Maximized EMU Ground Activity Certification Program. In place since 1993, the Availability Plan is a comprehensive program through which NASA evaluates the capability of EMU hardware to operate beyond the suit's original 15-year design life. The Availability Plan outlines life extension and refurbishment activities through 2028 and specifies the repair and replacement cycles for the EMU's PGS and PLSS components.[6]

The Maximized EMU Ground Activity Certification Program was instituted in 2006 and includes EMU repair and refurbishment activities. NASA performs ground maintenance on each EMU after 6 years on-orbit or 25 EVAs, whichever comes first. As part of the certification process, technicians periodically strip and recoat the aluminum water tank structure, dip the valve module in a solvent for cleaning, and thoroughly clean and refurbish the sublimator. The remaining components are checked for limited life and operation, and the reassembled spacesuit undergoes a vacuum certification process that includes 24 hours of unmanned operation in a vacuum chamber. Most of these repair and refurbishment activities are completed at processing facilities in Houston, Texas, and Windsor Locks, Connecticut. However, certain maintenance procedures, such as replacing the fan pump separators, have been done on-orbit.

Next-Generation Spacesuit Design Efforts

Although the capabilities of NASA's current EMU are adequate for ISS use, the spacesuit will not meet the needs of the Agency's deep space exploration plans. For example, the current EMU lacks the hip flexibility needed to walk on and explore planetary surfaces. Depending on the mission and the targeted extraterrestrial body, a variety of factors must be taken into account when creating a spacesuit for deep space environments, including the design of the vehicle in which the astronauts will travel and the pressures, atmospheres, temperatures, and dangers of the places they will visit. For more information on these considerations, see Appendix C.

Over the past 8 years, NASA has managed three separate spacesuit development efforts intended to support future missions – Constellation Space Suit System (CSSS), Advanced Space Suit Project, and Orion Crew Survival System (OCSS). As of April 2017, none of these efforts have delivered a flight-ready spacesuit. Figure 2 summarizes key information about each of the efforts. Congress has also expressed an interest in these efforts, as the NASA Transition Authorization Act of 2017 directs the Agency to submit to Congress a plan for "achieving an advanced spacesuit capability that aligns with the crew needs for exploration enabled by the Space Launch System and Orion, including an evaluation of the merit of delivering the planned suit system for use on the ISS."[7]

[6] PGS components are typically replaced every 8 to 10 years. In contrast, NASA typically refurbishes rather than replaces PLSS components.

[7] NASA Transition Authorization Act of 2017, Pub. L. No. 115-10 (2017).

Figure 2: NASA's Spacesuit Development Efforts

	Constellation Space Suit System	Advanced Space Suit Project	Orion Crew Survival System
Program/project	Constellation Program/ EVA Project	Advanced Exploration Systems Division/Advanced Space Suit Project	Orion Program/OCSS
Areas of emphasis	Launch, entry, and abort suit, and EVA PGS and PLSS prototypes	EVA PGS and PLSS prototypes	Launch, entry, and abort suit and associated equipment
Status	contract ended	in development	in development
Prime contractor	Oceaneering International, Inc.	NASA (in-house)	NASA (in-house)
Dates in use/ development	2009 through January 2016	2007 to present[a]	2012 to present
Cost	$135.6 million	$51.6 million	$12 million

Source: NASA Office of Inspector General (OIG) analysis of NASA information.

Note: Photos for each effort are of the PGS only and do not represent the entire set of deliverables.

[a] Technology that later became a part of the Advanced Exploration Systems Division's Advanced Space Suit Project began in 2007 under the Exploration Technology Development Division, and transferred to the Project in 2012. In fiscal year 2016, responsibility for further advancement of these technologies was transferred to the EVA Office.

Constellation Space Suit System

NASA established the Constellation Program in response to the NASA Authorization Act of 2005, which called for the development of a crew exploration vehicle, crew launch vehicle, and heavy-lift launch vehicle, and a return to the Moon as a stepping-stone to future exploration of Mars and other destinations.[8] Starting in early 2005, NASA's Advanced Extravehicular Activity Project Office began examining potential spacesuit architectures for the Constellation Program. As a result of this effort, in 2009, NASA issued a contract worth up to $148 million to Oceaneering International, Inc. to develop and produce the CSSS. However, in October 2010, the Constellation Program was canceled. After cancellation, NASA officials opted to continue portions of the contract to develop spacesuit technologies, and the contract remained active until January 2016. Between 2009 and the end of the contract, NASA paid Oceaneering $135.6 million. Oceaneering delivered design data and components of spacesuit hardware – such as the prototype PGS pictured in Figure 2 – to NASA over the life of the contract.

[8] NASA Authorization Act of 2005, Pub. L. No. 109-155 (December 30, 2005).

Advanced Space Suit Project

Since 2007, NASA has spent a total of $51.6 million through fiscal year (FY) 2016 on technologies in support of the Advanced Space Suit Project.[9] The technologies the Project is developing are intended for use in all the destinations envisioned in NASA's Journey to Mars framework, including cislunar space, a Martian moon, and the red planet itself. To date, the Project has developed two prototype PGSs – the Z-1 and the Z-2 – and is working on integrating the Z-suit with a newly developed advanced portable life support system for testing.

Z-Series Pressure Garment System. The first Z-Series pressure garment system prototype – the Z-1 PGS, which cost NASA $1.8 million – consisted of separate efforts by Oceaneering International, Inc. and ILC Dover that were later integrated by NASA.[10] Featuring rear entry and a soft upper torso, the Z-1 PGS provided increased mobility through modified shoulder and hip joints and the ability to operate at different pressures. The Z-1 PGS was compatible with "SuitPort," an interface between the interior of a space vehicle and the spacesuit that is mounted on the exterior of the vehicle and allows for more rapid entry and exit of the spacesuit and less time spent preparing the spacesuit for spacewalks.[11]

Procured from ILC Dover for $5.5 million and delivered in 2016, the Z-2 PGS featured numerous upgrades from the EMU and Z-1.[12] For example, whereas the EMU is configured for microgravity operations and thus has no lower body mobility, the Z-2 featured increased upper and lower mobility to allow astronauts to walk over rough terrain, kneel and pick up objects, and rise from a supine position, all activities needed for future exploration missions. The Z-2 also included weight reduction technologies and a composite upper torso.

Advanced Portable Life Support System. The Advanced Space Suit Project developed two iterations of an advanced portable life support system for use with the Z-series PGS – the PLSS 1.0 and PLSS 2.0; is working on a third – PLSS 2.5; and had planned for a fourth version – PLSS 3.0 (see Table 1).

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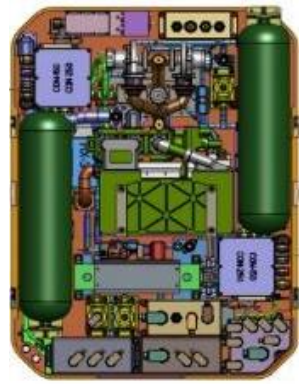
9 After the Constellation Program was canceled, the Advanced Space Suit Project became NASA's primary spacesuit technology development effort. Several key technologies were developed under the Exploration Technology Development Program and Exploration Technology Development Division before being incorporated into the EVA system development efforts of the Advanced Exploration Systems Division – a division of the Human Exploration and Operations Mission Directorate – beginning in FY 2012.

10 The Z-1 upper torso assembly was procured under the CSSS contract through Oceaneering International, Inc. and the lower torso was developed by ILC Dover under suit technology development within NASA's Exploration Technology Development Program.

11 The Z-1 spacesuit featured rear entry with a SuitPort interface plate, nominal operating pressure of 8.3 pounds per square inch, and the ability to withstand SuitPort system loads while still providing surface suit mobility needs.

12 The primary purpose of the Z-2 was to mature the system towards a flight configuration. As such, the spacesuit was built to higher quality standards and could support human vacuum chamber testing.

Table 1: Advanced PLSS Comparison

	PLSS 1.0 (Breadboard)	PLSS 2.0 (Repackaged PLSS)	PLSS 2.5 (Unmanned Testing Prototype)	PLSS 3.0 (Human Rated Flight)
				
Purpose	Schematic validation and component integration	Packaged lab unit and system level performance	Flight design without paperwork, and integrated system performance	Detailed test objective *(not yet developed)*
Hardware	• Prototype oxygen pressure regulation, heat removal, ventilation flow, and carbon dioxide removal components • Remaining components commercial off-the-shelf	• Second-generation prototype oxygen pressure regulation, heat removal, and carbon dioxide removal components • First-generation remaining components	• Third-generation prototype oxygen pressure regulation, heat removal, and carbon dioxide removal components • Second-generation ventilation flow and remaining components	• All final elements for use as an ISS EMU replacement
Testing	• 8 simulated EVA profiles • 397 hours of PLSS operation	• 19 pounds per square inch air human-in-the-loop testing • 25 EVA tests at vacuum	• 100 unmanned EVAs in vacuum • Vibration testing • Magnetic and electromagnetic testing • Unmanned thermal vacuum testing	• 100 unmanned EVAs in vacuum • Vibration testing • Magnetic and electromagnetic testing • Human thermal vacuum testing[a]

Source: NASA OIG summary of Agency information.

[a] In addition to tests listed, PLSS 3.0 would also perform integrated testing with the PGS, to include manned thermal vacuum testing.

The PLSS 1.0 cost $11 million to develop and featured a room-sized "breadboard" system used to validate advanced technologies for carbon dioxide and humidity removal, pressure control, and a more water-contamination-tolerant thermal control device.[13] For the PLSS 2.0 – completed in September 2013 for $11.3 million – the room-sized system was repackaged into a smaller, wearable unit.

[13] A "breadboard" is a circuit assembled on an insulating surface, often with solderless contacts, in which components can easily be replaced for alteration and experimentation. Breadboards also allow for different subsystems to be changed out to test their functions in an integrated system.

Currently, the Advanced Space Suit Project is developing the PLSS 2.5, on which NASA has spent $16.3 million through FY 2016. The PLSS 2.5 includes a smaller, lighter carbon dioxide removal system that can regenerate itself, lessening the weight astronauts must carry and allowing for longer EVAs. It also features an improved oxygen system with a variable pressure set point regulator and on-orbit rechargeable secondary oxygen supply tanks to enable flexibility and real-time changing of suit pressure. In addition, rather than crossing the water and ventilation loops as in the EMU, the PLSS 2.5 employs an updated carbon dioxide and humidity removal component that will allow for separation of the water and ventilation loops and therefore prevent the intrusion of water into astronaut helmets. The PLSS 2.5 is also being designed for a minimum operating life of 1,000 hours to support 100 EVAs at 8 hours per EVA and 2 hours of spacesuit donning and doffing, an improvement over the current EMU's 7 hour per EVA maximum. A prototype of the PLSS 2.5 is expected to be available in 2018. Plans to develop PLSS 3.0 have been revised.

Power, Avionics, and Software Subsystem. The Advanced Exploration Systems (AES) Division's Advanced Space Suit Project also funded and developed an advanced power, avionics, and software subsystem to maintain and monitor spacesuit systems at a cost of $5.6 million through FY 2016. This subsystem provides power supply and distribution for the overall EVA system, collecting and transferring several types of data to and from other mission assets, providing avionics hardware to perform numerous data displays and in-suit processing functions, and furnishing information systems to supply data to enable crew members to perform their tasks with autonomy and efficiency. Until 2016, when all spacesuit development activities were consolidated at Johnson Space Center (Johnson), Glenn Research Center (Glenn) was involved in development of the EMU's power, avionics, and software subsystem. Work at Glenn focused on the Informatics System, which included a heads-up display rather than a cuff display, a processor located in the PLSS, a high-definition camera mounted above the shoulder, and an audio system integrated into the spacesuit rather than worn as a headset. Much of this work was in the early stages of development but has been postponed in favor of the Agency's new spacesuit plans.

Future Spacesuit Development Plans. The next iteration of the PLSS for the Advanced Space Suit Project was supposed to be PLSS 3.0. However, in November 2016, NASA revised its plans in favor of a potential three-stage development effort that focuses on development of the Exploration EMU (xEMU) Lite – a spacesuit that could replace the EMUs currently used for EVAs from the ISS. The xEMU Lite will be followed by the xEMU for cislunar space missions, and finally the Mars EMU (mEMU) for Mars surface exploration. The xEMU Lite plan – in which a simplified exploration PLSS and Hard Upper Torso are integrated with the current EMU's lower torso, arms, gloves, and boots – includes further refinement and testing of PLSS technologies such as the carbon dioxide removal system. ISS Program officials told us that because of the high cost of replacing the entire spacesuit, this plan is the lowest cost option for testing new spacesuit technology that could replace the aging fleet of EMUs. The plan will also allow advanced PLSS technology to be tested on the ISS before it is used on deep space exploration missions. However, Program officials noted that while this should be sufficient for testing individual technologies and may extend ISS EVA capability, the plan does not serve as a test bed for any future EVA system as a whole.

Orion Crew Survival System

The OCSS – a launch, entry, and abort spacesuit for the Orion Multi-Purpose Crew Vehicle (Orion) – was originally developed by NASA civil servants as a "smart buyer" effort pursuant to which civil servants develop technology the Agency uses as the basis for procuring goods or services from a private contractor. The purpose of the spacesuit was to protect astronauts from fire, smoke, or toxic chemicals in the event of a launch pad abort in which the crew must flee a compromised vehicle as well as to provide a redundant pressurized atmosphere in case of an issue with the primary vehicle systems. The spacesuit is a derivative of the launch, entry, and abort spacesuit used during the Space Shuttle Program – the Advanced Crew Escape System (ACES) spacesuit.[14]

Beginning in 2009 and using Johnson's support contracts and components from the Space Shuttle's ACES and Apollo era inventories, NASA civil servants developed a launch, entry, and abort system, which was the precursor to OCSS. Using NASA employees and existing engineering contracts to develop the spacesuit was seen as more cost-effective than the launch, entry, and abort spacesuit that was being developed under the CSSS contract, and between 2010 and 2016 NASA spent approximately $12 million on the system. In contrast, over that same time period, the Agency expended an average of $18 million per year for the more limited work that occurred under the CSSS contract. Development work is continuing towards Preliminary Design Review in June 2017 and Critical Design Review in the summer of 2018, and fabricated flight suits are expected to be delivered for Exploration Mission-2 in 2021.[15]

Management of NASA's Spacesuit Portfolio

In the past, NASA linked spacesuit development efforts to specific programs like Mercury, Apollo, and the Space Shuttle. However, with the exception of the OCSS spacesuit, recent spacesuit development efforts have not followed this practice. Instead, the spacesuits have been developed separately without a specific mission in mind.[16] Multiple directorates at Johnson assist in both the developmental efforts of advanced EVA hardware and the maintenance and operations of the current fleet of EMUs. Figure 3 shows the primary offices responsible for development and operation of EVA hardware. These include the EVA, Robotics, and Crew Systems Operations Division within the Flight Operations Directorate, the EVA Office within the Exploration Integration and Science Directorate, and the Spacesuit and Crew Survival Systems Branch within the Engineering Directorate.

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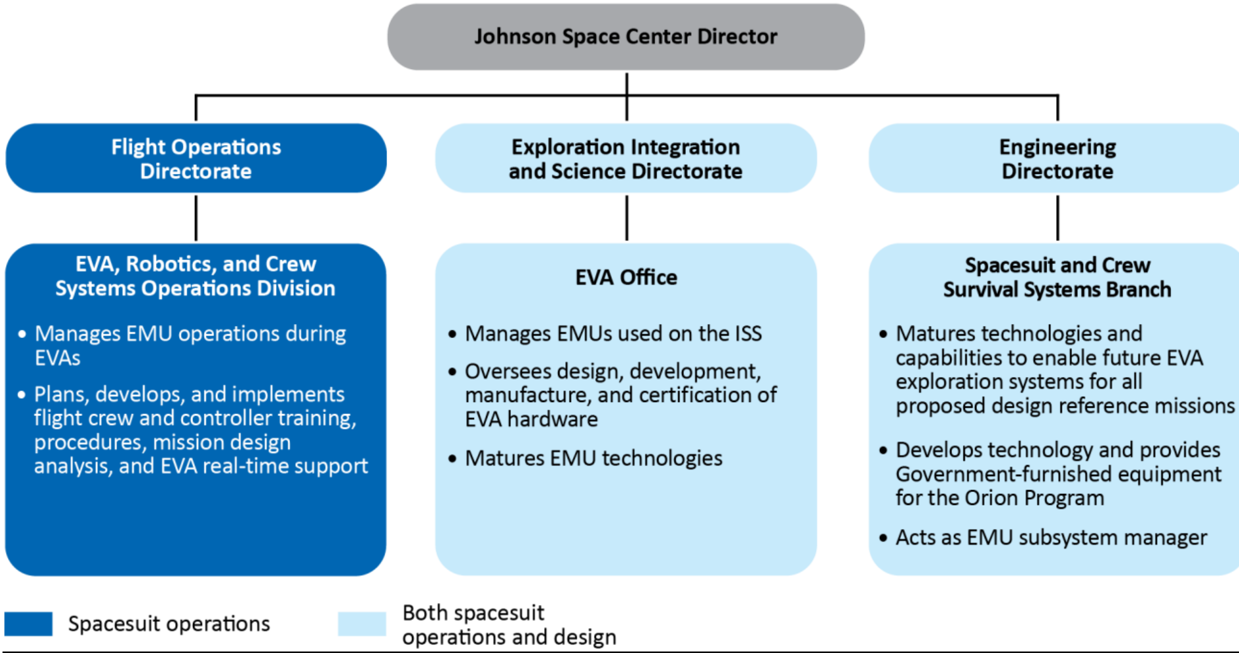
[14] ACES, an orange-colored launch, entry, and abort spacesuit developed in 1990 and used from 1994 until the end of the Space Shuttle Program, and was a full pressure unit that contained a parachute and flotation system in case of crew bailout and provided an atmosphere in the event of vehicle decompression.

[15] The Preliminary Design Review demonstrates that the design meets all system requirements with acceptable risk and within cost and schedule constraints and establishes the basis for proceeding with detailed design. A Critical Design Review is held to determine whether a design is sufficiently mature to proceed to full-scale fabrication, assembly, integration, and testing and whether the technical effort is on track to meet cost and schedule commitments. Under NASA's current plans, Exploration Mission-2 will be the Agency's first crewed mission beyond low Earth orbit since the 1970s. However, the Acting Administrator announced in February 2017 that he directed Agency spaceflight officials to study the feasibility of adding crew to Exploration Mission-1, a previously uncrewed mission scheduled to launch in late 2018 that would be the first flight of the integrated Space Launch System and Orion capsule.

[16] Program officials assert that although there is no specific mission, NASA nevertheless is employing a capability driven approach, thus enabling the EVA technology development community to press forward with years of lessons learned, known exploration mission classes, and lists of identified technology gaps to guide the advancement of the technologies.

Figure 3: Spacesuit Management Offices



Source: NASA OIG analysis of Johnson operations.

Two different offices at Johnson support the maintenance and operation of NASA's current fleet of EMUs. The EVA, Robotics, and Crew Systems Operations Division, part of the Center's Flight Operations Directorate, manages EMU-related operations during spacewalks. This division is responsible for planning, developing, and implementing flight crew and flight controller training, procedures, mission design analysis, and real-time support for EVAs for the ISS Program. Meanwhile, the EVA Office, part of the Center's Exploration Integration and Science Directorate, manages the EMUs and oversees the design, development, manufacture, and certification of all EVA hardware.

The Engineering Directorate's Spacesuit and Crew Survival Systems Branch coordinates with AES (both at Johnson and at NASA Headquarters) and the Space Technology Mission Directorate to mature technologies and capabilities that will enable future EVA exploration systems, including developing the Z-1 and Z-2 spacesuits and the PLSS 1.0, 2.0, and 2.5. Additionally, the Branch provides technology development support and Government-furnished equipment to the Orion Program for the OCSS and serves as the ISS Program's primary agent for identifying and resolving technical issues associated with EMU performance. AES's Advanced Space Suit Project was developing spacesuit technology parallel to the EVA Office's CSSS contract activities until 2016, when development efforts were consolidated under the EVA Office.

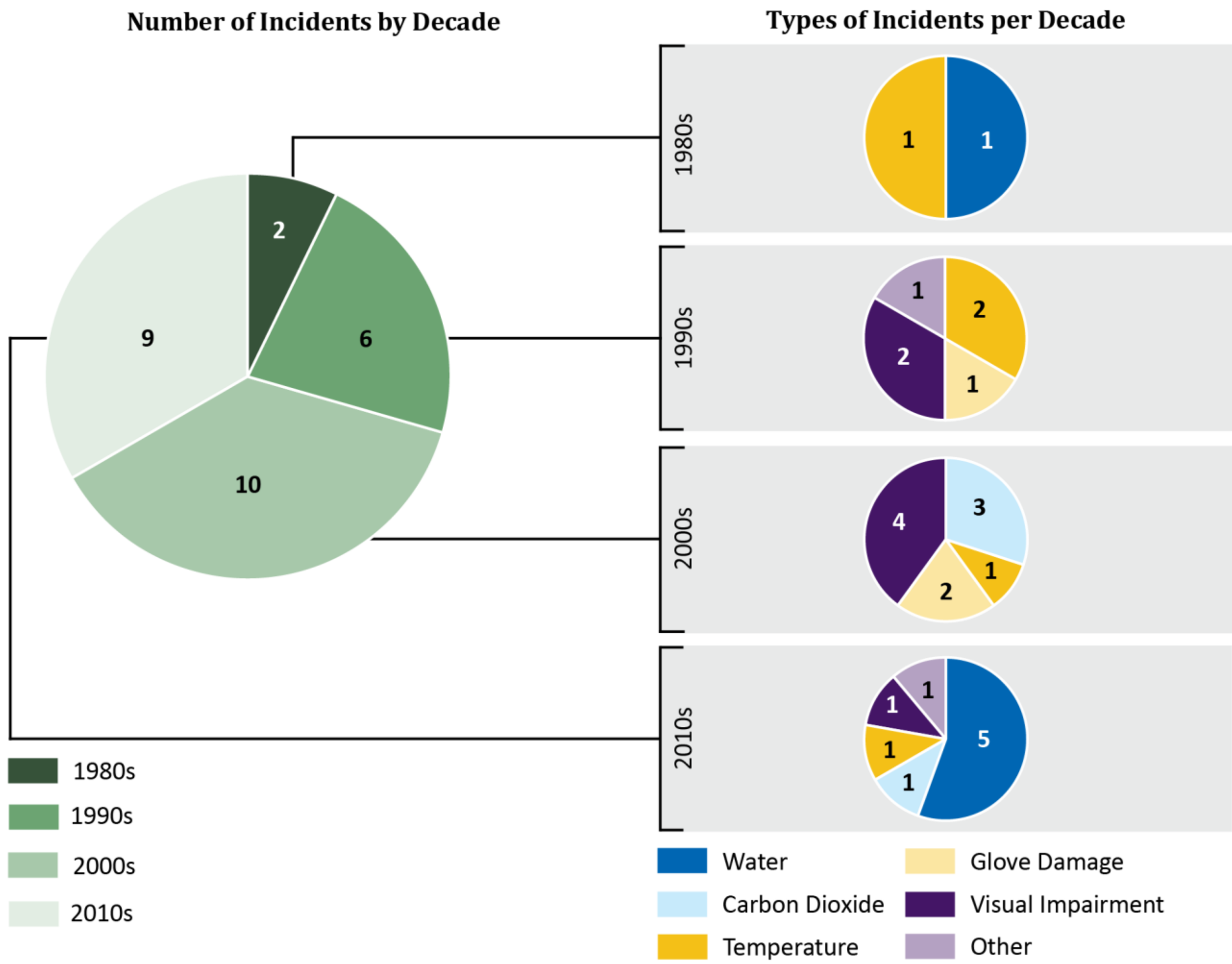
EMU Anomalies and Significant Incidents

From the beginning of design and fabrication in the 1970s through April 2017, there have been more than 3,400 anomalies in EMU maintenance and operations both on the ground and on-orbit.[17] These

[17] An anomaly includes any type of hardware or software performance that is not expected or called for, a violation of flight rule constraints, or a facility issue.

anomalies are typically minor issues like a loose boot thread, a minor display and control module issue, or the peeling of a special coating from the outside of the gloves. In the same time period, astronauts have performed 204 spacewalks wearing the EMUs and have experienced 27 "significant incidents," including glove damage, uncomfortable body temperatures, and helmet water intrusions.[18] None of these incidents resulted in the death or permanent injury of an astronaut, and only five resulted in the early termination of the EVA. Figure 4 shows the overall number of incidents and groups them by categories and decade.[19]

Figure 4: Reported EMU Significant Incidents by Decade



Source: NASA OIG analysis of Johnson Safety and Mission Assurance Flight Safety Office data.

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[18] Johnson's Office of Safety and Mission Assurance, Flight Safety Office classifies a "significant incident" as an event that resulted in or could have resulted in loss of life, resulted in the injury or temporary incapacitation of an astronaut or otherwise compromised the astronaut's ability to perform critical tasks, resulted in the potential for critical or catastrophic damage to spacecraft, caused a spacewalk to be aborted or terminated early, or has some other unique significance. We used data collected by the Flight Safety Office regarding reported events during spacewalks and the criteria set forth in the Office's white paper "Significant Incidents and Close Calls in Human Spaceflight: EVA Operations" to arrive at this figure. (NASA, "Significant Incidents and Close Calls in Human Spaceflight: EVA Operations," July 27, 2016.) There is no consensus across NASA regarding the definition of a significant incident.

[19] During this period of time, a total of 204 EVAs were performed: 13 between 1983 and 1989, 35 between 1990 and 1999, 113 between 2000 and 2010, and 43 since 2010.

The six broad categories of significant incidents are as follows:

- *Water.* The six incidents dealing with water – five of which occurred in the 2010s – fall into two subcategories: water intrusion and fog or condensation.[20]
- *Carbon dioxide.* Three of the four incidents related to carbon dioxide occurred in the 2000s when elevated carbon dioxide levels were detected in the spacesuit.[21]
- *Temperature.* Although astronauts have liquid cooling garments and warmers in their spacesuits, sometimes the temperature of their spacesuits can get too cold, causing discomfort to the astronaut, or too warm, resulting in helmet fogging.[22]
- *Glove damage.* Three incidents related to glove damage, which is a part of the astronauts' PGS – a system identified as single-fault tolerant that could result in the termination of an EVA and potential activation of the secondary oxygen pack if the hole is large enough.[23]
- *Visual impairment.* More prevalent in the 2000s, these incidents included burning or stinging in the eyes or debris entering astronauts' eyes.[24]
- *Other.* The remaining incidents involved communications issues because of lost audio reception and the accidental flooding of a sublimator that required a two-week dry out period for the spacesuit because subsequent exposure to the vacuum of space would have resulted in ice formation and damage of the thermal regulation device.[25]

Although there does not appear to be any trend with the total number of significant incidents over time, reported anomalies have nonetheless been prevalent over time. Accordingly, in 2016 the EVA Office initiated an analysis of all failures between 2013 and 2015 that impacted EVA availability on the ISS, the most notable of which was EVA 23. On this EVA, the astronaut reported that a large amount of water in his helmet affected his ability to breathe and interfered with visibility and communications. The study found that recent spacesuit failures are largely associated with EMU water quality sensitivity and

[20] Two of the water intrusion incidents included EVA 23 and its precursor EVA 22, when water first appeared in the helmet that was later used on EVA 23. The remaining water related events involved the condensation of humidity on astronauts' helmets because of inefficient water separation in the PLSS or elevated body temperatures.

[21] Two of these events occurred towards the end of the EVA and did not impact the completion of required tasks, but one incident resulted in the termination of the EVA with uncompleted tasks. In the remaining incident, the carbon dioxide sensor gave an error message and biomedical data on the spacesuit was lost, which means if the astronaut had been exposed to carbon dioxide, the sensor would have been unable to provide an early warning of the increased levels.

[22] There were two incidents of astronauts becoming too cold during the 1990s, one of which resulted in the termination of an EVA. After 2000, two incidents occurred involving the operation of the sublimator and unexpected water temperatures, after which the PLSS units could not be used until they were returned to the ground for inspection.

[23] Because sharp edges on the ISS can tear their gloves, astronauts perform multiple glove checks throughout the course of EVAs. If tears are found, the EVA will be terminated. If the secondary oxygen pack on the spacesuit is activated, the PLSS cannot be used again until it is returned to the ground for maintenance.

[24] In total, three of the incidents involved water from the disposable drink bag getting into astronauts' eyes and irritation from the anti-fog chemical used in astronauts' helmets. The remaining four incidents either involved eye irritants unrelated to the disposable drink bag or the failure of the helmet's light assembly. If debris is found in a spacesuit on the ISS, astronauts thoroughly inspect the suit for the source. If the source is not found, the spacesuit cannot be used until after it is returned to the ground for processing.

[25] Although there was no resulting damage to the spacesuit and another PLSS was utilized for remaining spacewalks, there was an impact on EMU availability for the time while the spacesuit dried out.

limitations in conducting on-orbit repairs and maintenance.[26] However, EVA and Flight Safety Office officials also said that the increase in reported water incidents could be attributed to increased sensitivity to the issue after EVA 23.

Generally, NASA has tried to prevent recurrence of hardware failures and other issues that have led to significant incidents by ensuring adherence to flight rules, improving spacesuit design, removing EMUs from the rotation when necessary, and implementing additional policies and procedures to ensure astronaut safety.[27] For example, in 2007 when an astronaut discovered a cut in the outer layers of his glove, the EVA was terminated and NASA redesigned the gloves with a more durable material.

EVA Water Intrusion Incidents

As discussed, since 2013 NASA has experienced three significant incidents of water intrusion in EMU helmets. In July 2013, during EVA 23, a European Space Agency astronaut reported a growing "blob" of water in his helmet, leading to early termination of the EVA. When the spacesuit was removed, the crew found between 1 and 1.5 liters of water in the helmet. Because the incident could have been fatal, NASA classified it as a High-Visibility Close Call.[28]

Recreation of Water Intrusion Incident Experienced During EVA 23

Source: NASA.

NASA appointed a Mishap Investigation Board to determine the cause of the incident that occurred during EVA 23 and examine Mission Control's response. The Board determined that "cultural complacency" – becoming content and erroneously confident in one's duty or knowledge – may have played a role in the mishap. This finding was based on the response to the discovery of water in the same helmet after EVA 22, the previous spacewalk.[29] In that case, officials concluded the water had come from a leaking drink bag and simply replaced the bag without conducting adequate tests to confirm their conclusion. According to the Board, had the EVA community (which includes crew members onboard the ISS and team members from Operations, Engineering, and Safety) investigated the water source more thoroughly – a simple test of the drink bag would have taken only about 10 minutes – the EVA 23 incident could have been avoided.

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[26] The EVA Office has initiated a more complete statistical study of spacesuit failures with results expected in summer of 2017.

[27] Flight rules document the authority and responsibility of all organizations involved in the conduct of mission operations, responses to contingency situations, and operational philosophy and direction with respect to operational and programmatic priorities, safety and mission success, and failure tolerance during NASA aerospace and aviation events.

[28] A High-Visibility Close Call is an event in which there is no injury or only minor injury requiring first aid, no damage or minor damage (less than $20,000) to equipment or property or both, but which possesses the potential to cause a mishap that the Administrator; Chief, Safety and Mission Assurance, Office of Safety and Mission Assurance; Center Director, Executive Director, Office of Headquarters Operations; or Center Safety and Mission Assurance Director judges to possess a high degree of safety risk, programmatic impact or public, media, or political interest.

[29] The Mishap Investigation Board found four other operational causes for the water intrusion: (1) because of the ISS Program's focus on using on-orbit time for science, lower-level Mission Control team members did not take sufficient time to investigate the EVA 22 water intrusion; (2) the Flight Control team believed reporting and investigating the anomaly during EVA 22 would take too much time and would delay EVA 23, which was scheduled for the following week; (3) the behavior of water in zero gravity was not understood; and (4) the team did not appreciate the hazards of water intrusion because they had come to believe that such intrusions were normal.

The ISS Program also initiated an investigation separate from the Mishap Board to determine the root cause of the EVA 23 incident. This investigation concluded the water had accumulated because inorganic materials had blocked holes in the EMU's water separator, allowing water to spill into the ventilation loop that circulates air into the helmet. The investigation also found the buildup of inorganic matter occurred because a water filtering facility at Johnson had not been managed to control for silica. As a result, silica-laden water was used in the processing of flight hardware filters that later was used in four on-orbit spacesuits.

As a result of these investigations, the EVA Office and ISS Program are implementing 210 recommendations ranging from utilization of a helmet absorption pad and snorkel to actions to combat cultural complacency.[30]

After the EVA 23 High-Visibility Close Call, the ISS Program implemented cultural complacency studies, initiated new training procedures to practice responses to emergency and major failure scenarios, and required documentation of all on-orbit instances of free water in anomaly reports. Two and a half years later, during EVA 35 when a NASA astronaut reported feeling water in his helmet, ground control officials promptly terminated the EVA. Subsequent investigation found that perspiration resulting from high body temperatures in the airlock during EVA preparations followed by a cold thermal environment in the shade early in the EVA likely caused the water buildup. In addition, clogged sublimator slurper holes were deemed a potential contributing factor.[31]

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30 The 210 recommendations consist of 108 actions from the ISS Emergency Recovery Team, 49 from the Mishap Investigation Board, 27 from the ISS Program, 18 from the Independent Review (the ISS Emergency Recovery Team chair asked for a separate Independent Review to determine if the Team was headed in the right direction), and 8 from the NASA Engineering and Safety Center. As of April 2017, 188 of the 210 recommendations had been closed.

31 The slurper is a plate with holes in the sublimator through which condensed water and some gas flows into the water separator where water is separated from gas. The water is then returned to the cooling loop or feedwater tanks and the gas to the ventilation loop.

NASA Faces an Array of Risks in Sustaining Current Spacesuits for Use on the ISS

NASA continues to manage an array of design and health risks associated with the EMUs. In addition, only 11 of the 18 original EMU PLSS units are still in use, raising concern the inventory may not be adequate to last through planned retirement of the ISS in 2024. Given these issues, NASA will be challenged to continue to support the EVA needs of the ISS with the current fleet of EMUs through 2024 – a challenge that will escalate significantly if Station operations are extended to 2028.

NASA's Efforts to Mitigate EMU Design and Health Risks

When NASA was using the Space Shuttle to transport astronauts to and from the ISS, the EMUs were returned to Earth after every mission, examined for any defects or other issues, and necessary maintenance was performed. However, since the Shuttle's retirement in 2011, NASA has had limited ability to return the EMUs from the ISS because only one of the commercial vehicles that ferry supplies to the Station has the capability to return items to Earth. Consequently, NASA adopted the current maintenance cycle pursuant to which the EMUs are certified for 6 years or 25 EVAs, whichever comes first. As a result, astronauts are using the EMUs for much longer periods of time between maintenance and refurbishment than originally intended. Table 2 details the evolution of the EMU ground maintenance intervals from the time the spacesuits were first used during the Shuttle Program until the last review in 2008.

Table 2: EMU Certification and Ground Maintenance History

Year	EMU Certification and Ground Maintenance Timeframe
1982	Certified for a single Shuttle Mission
1995	Certified for 25 EVAs over 180-day period to support ISS assembly
2000	Ground maintenance interval extended to 1 year
2003	Ground maintenance interval extended to 2 years
2007	Ground maintenance interval extended to 3 years
2008	Ground maintenance interval extended to 6 years, with in-flight maintenance and additional ground processing

Source: NASA OIG analysis of EVA Office information.

In August 2016, an independent technical review team commissioned by the ISS Program found the 6-year maintenance interval and 25 EVA certification process valid, but noted several limitations and identified potential improvements. For example, the report noted that EMU rotations do not occur as frequently as originally planned due to launch slips, launch failures, and hardware failures. As a result, the EMUs regularly exceed the 6-year maintenance interval, with one EMU recently extended to almost

9 years – a nearly 50 percent schedule slip to the planned maintenance schedule. The review team suggested several improvements to the process, including developing a comprehensive one-page explanation of the EMU life limits and maintenance intervals and studying the possibility of developing procedures and hardware to prevent disturbing evidence after failures.[32]

EMU Design Inadequacies

The EMU was originally designed to be brought into space, used several times, and brought home for maintenance and refurbishment. However, the retirement of the Shuttle Program required a new maintenance program. Currently, the spacesuits are operating in a different environment onboard the ISS with longer periods between refurbishment and some maintenance tasks performed on-orbit. This has made several of the EMU's design inadequacies more prominent, including four notable shortfalls for which NASA must control when conducting EVAs from the ISS.

Crossed Water and Ventilation Loops

In order to save space and weight in the EMU, the water and ventilation loops are crossed, which has resulted in multiple incidents of water intrusion into the helmet. To address this issue, NASA has added specific procedures to astronauts' EVA cuff checklists, installed a pad in the helmet to absorb excess water, and installed a snorkel to provide an alternative means of breathing in case of water intrusion.[33]

Components Sensitive to Water Contamination

As discussed previously, the EVA 23 Mishap Investigation Board found that the water intrusion during that incident occurred because inorganic materials blocking the drum holes in the EMU's water separator allowed water to spill into the ventilation loop that circulates air into the helmet. In addition, Program officials described multiple incidents of a contaminated sublimator resulting in issues with cooling the suit. To mitigate the risk of a reoccurrence, NASA issued a Program Technical Directive requiring all contamination and corrosion found during ground processing of the EMUs be documented, traced, and discussed. The Agency also conducts analysis of any water that enters the EMU and performs regular water quality testing.

Several EMU Systems Do Not Meet Fault Tolerance Requirements for ISS Systems

The ISS was developed with a requirement that every system tolerate at least two faults without resulting in a failure that could cause loss of crew or vehicle.[34] However, the Shuttle Program did not have a similar fault tolerance requirement and therefore several EMU systems do not comply with this requirement. For example, when the carbon dioxide filter reaches the end of its life, an astronaut can eliminate expired air from the spacesuit by opening a valve that lets the air out into space. However, this can lead to higher oxygen consumption rates and potential activation of the secondary oxygen pack,

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[32] The one-page summary includes illustrations communicating EMU life limitations and maintenance interval requirements to the EMU community and external audiences. The summary also notes that defined life limits are not a guarantee against hardware failures.

[33] The EVA cuff checklist, worn below the left elbow of the EMU, contains procedures and reference data for performing EVA tasks. The checklist also contains procedures that aid in the diagnosis and resolution of an EMU failure.

[34] NASA Procedural Requirements 8705.2B, "Human-Rating Requirements for Space Systems," May 6, 2008.

which renders the spacesuit inoperable until it is returned to the ground for inspection and any necessary maintenance.[35] Although the EMU includes a carbon dioxide sensor for estimating the life of the carbon dioxide filter, the sensors are susceptible to water, with some failing after exposure to perspiration. To mitigate this issue, NASA provides astronauts with a 30-minute reserve supply of oxygen in a separate system and procedures to ensure they can return to the Station within that timeframe in the event of an EMU failure.

EMU PLSS Not Designed to be Maintained On-Orbit

The EMU was designed with short mission durations in mind and to be serviced on the ground after every Space Shuttle mission. As noted earlier, the suits are no longer routinely returned to Earth and therefore some maintenance tasks are performed by astronauts on Station. To mitigate this risk, NASA provides ground training and on-orbit instruction for astronauts through video training that enables them to perform minor repairs until an EMU can be returned to Earth for more extensive ground processing. However, these measures take considerable crew time and reduce the time astronauts can dedicate to research activities.

EVA Health Risks

Despite the Agency's efforts to mitigate the EMU's design inadequacies, astronaut health risks remain. Apart from the water intrusion and carbon dioxide issues noted earlier, NASA tracks two other primary risks: decompression sickness and thermal regulation. In addition, other less severe risks caused by the spacesuits include shoulder injuries, hand injuries, and insufficient nutrition and hydration.

Lengthy Pre-Breathe Procedures Prevent Decompression Sickness

As of April 2017, NASA has had no reported case of decompression sickness during flight as a result of using its "pre-breathe" procedures. Decompression sickness, which can result in shock; circulatory collapse; burning or prickling sensations in the hands, arms, legs, or feet; rashes and swollen skin; air bubbles in the blood; blockage of blood vessels; and even death, has the potential to occur when astronauts move from the atmosphere of the Station, which has a higher partial pressure of nitrogen (approximately 11.6 pounds per square inch), to the lower pressure inside an EMU (approximately 4.3 pounds per square inch). Pre-breathe procedures prior to an EVA prepare astronauts for this transition by exposing them to an enriched oxygen environment (with a lower pressure of nitrogen) during rest or exercise. These procedures, which help reduce the amount of nitrogen in the body and therefore the potential for dangerous gas bubbles to form in the circulatory system, take from 4 to 12 hours depending on the specific protocol.

An alternative to performing pre-breathe procedures prior to a spacewalk is to create a higher-pressure spacesuit. However, with current EMU technology, especially the design of the gloves, increasing pressure in the suit would decrease astronaut mobility and cause the crew to tire more quickly. Accordingly, increased pressure is not an option with the current EMUs. Going forward, technologies developed by the Advanced Space Suit Project may enable development of a higher-pressure spacesuit without the corresponding fatigue and reduced mobility. Although decompression sickness risks are

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[35] Since 1965, carbon dioxide has been a confirmed factor in four significant incidents.

currently mitigated for the ISS, future exploration programs will need to develop and validate new pre-breathe procedures to accommodate the increased decompression sickness risks associated with planetary EVAs such as increased energy expenditure during planetary spacewalks. Program officials stated this risk can be mitigated in the future with changes to suit and vehicle operating pressures.

EMU Components and EVA Operations Can Cause Uncomfortable and Dangerous Body Temperatures

Overheating and perspiration issues are known threats to EVA operations, and EVA crewmember workloads have to be planned to accommodate the capabilities of the EMU.[36] NASA has mitigated these risks by planning EVAs to limit overheating and providing cooling and ventilation garments with manual controls. However, since 1983 potential or actual overheating or extremely cool temperatures have caused five significant incidents. For example, in 2007 higher water temperatures for a particular EMU were noted throughout several EVAs, and during a third EVA, sublimator water temperatures were the highest seen in the Program. As a result of these incidents and because the sublimator showed signs of worsening heat transfer, that particular spacesuit was not used for the remainder of the mission.

Constrained Hard Upper Torso Sizing Limits Astronaut Participation and Can Lead to Shoulder Injuries

The current EMUs do not provide a sufficient range of sizes in the Hard Upper Torso component to accommodate astronauts whose body size may not align with historical measurements. This has resulted in two separate issues – (1) exclusion of astronauts who are too large or too small and (2) the potential for shoulder injuries because astronauts wear the tightest-fitting Hard Upper Torso possible in order to enhance mobility. The Hard Upper Torso was designed in the Shuttle era to accommodate a specific range of individuals and fabricated in three sizes: medium, large, and extra-large. However, over the years the astronaut corps has become more diverse and includes individuals that do not conform to the historical norm.[37] As a result, astronauts who do not fit comfortably into available suit sizes can have increased accessibility issues. For example, temperature is controlled through a rotary dial on the front of the EMU, which means smaller astronauts face visual and mechanical disadvantages that limit their ability to properly control suit temperature. In addition, a more tightly fitting Hard Upper Torso has been identified as a potential contributing factor in shoulder injuries related to putting on and taking off the suit. However, some Station crewmembers prefer working in a tighter fitting Hard Upper Torso because this fit offers a greater range of motion for the shoulder. According to a 2012 study, astronauts who performed more than five EVAs in their lifetime were twice as likely to have had shoulder surgery compared with astronauts who performed only one EVA, an issue partially attributed to the stress placed on the shoulder during EVA training activities in the suit and the shoulder compression that occurs when the Hard Upper Torso is donned or removed.[38] However, later research performed within NASA compared astronaut shoulder consultations and surgeries to an external

[36] NASA standards state that astronaut impairment begins when core temperatures increase more than 1 degree Fahrenheit above the average human body temperature of 98.6 degrees.

[37] The mismatch is more prominent in the ISS era because all crewmembers are now required to be EVA certified, unlike the Shuttle era in which crew could serve inside the Shuttle only and avoid performing EVAs.

[38] Rick Scheuring, "Shoulder Injuries in US Astronauts Related to EVA Suit Design," presented at the Aerospace Medical Association, San Diego, California (May 11, 2012).

age- and sex-matched population, and showed that both age and sex were risk factors for orthopedic shoulder consultation and surgery for both groups. Although male astronauts were referred to orthopedists more often than in the comparison population, surgery rates did not differ between the groups. As such, Program officials assert there is currently no statistical evidence to support a correlation between Hard Upper Torso fit and shoulder injury.

Gloves Cause Hand Fatigue and Injures

Hand injuries, ranging from small blisters and cuts to joint pain, are the most common type of injury astronauts experience during EVAs. Although the EMU glove has evolved over time to increase mobility, dexterity, and tactile sense, astronauts with smaller hands remain more likely to experience hand injuries. Additionally, several astronauts have experienced hand fatigue because of the EMU's internal pressure and limited glove mobility.

EMUs Do Not Provide Recommended Levels of Hydration and Nutrition

Potable water is necessary during EVAs to prevent dehydration and improve comfort. Although NASA's human-system standards suggest astronauts should drink 8 ounces of water per hour to prevent dehydration, the Disposable In-suit Drink Bag holds only 32 ounces.[39] Because a typical EVA can result in an astronaut wearing the EMU between 9 and 10 hours, this results in a shortage of up to 48 ounces of water. In addition, NASA's standards require a food system to provide 200 kilocalories per EVA hour.[40] NASA formerly provided fruit bars in the EVA helmet, however this practice was discontinued because the bars were difficult for astronauts to access, time intensive to prepare, and sometimes smeared on the surface of the helmet and impaired visibility when they were not completely consumed. Although deviation from these standards has not been a significant issue for ISS EVAs, ensuring adequate hydration and nutrition may be a larger concern in the harsher environments of deep space.

Current Inventory of EMUs Low

The ISS Program expressed confidence that the current fleet of EMUs will be sufficient to provide EVA capability through 2024. Although EVA Office officials acknowledged that additional spacesuit attrition could impact the Program and cited the loss of additional EMUs due to launch failures or other non-repairable damage as the biggest risk, they believe a small number of losses would not affect the Program. Nevertheless, the two highest tracked EVA risks related to the ISS Program are EMU failures affecting EVA capability and EVA support through 2028.[41] Both programmatic risks are considered highly likely and of high consequence.

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[39] NASA-STD-3001, Vol. 2, § 11.2.3, "NASA Space Flight Human-System Standard Volume 2: Human Factors, Habitability, and Environmental Health," January 2011.

[40] NASA-STD-3001, Vol. 2, § 11.2.2.1. A kilocalorie is a unit of energy in food which is equal to 1,000 calories.

[41] The risk concerning EVA support through 2028 is primarily funding-related. ISS Program officials have expressed concerns there will not be sufficient funds to pay for EMU hardware through 2028. This concern has been partially alleviated by improved allocation of funds to EVAs over the next 4 to 5 years.

NASA originally built 18 EMU PLSS units. Five were destroyed during missions and one during ground testing.[42] In addition, one of the original suits was built for certification only and is not suitable for flight. Of the 11 remaining complete and functional spacesuits, 4 are kept on the ISS and the remaining 7 are on Earth in various stages of refurbishment and maintenance. According to Agency officials, procuring additional EMUs is not a viable option given the prohibitively high cost of the PLSS.[43] Table 3 shows the current status of all EMUs as of April 2017.

Table 3: EMU Flight Inventory Status as of April 2017

EMU PLSS Unit Serial No.	Current Location	Flight Ready	Reason
3001	Certification unit	No	Used for certification only.
3002	n/a	No	Destroyed in 1980 during ground testing.
3003	Onboard ISS	Yes	n/a
3004	UTAS	No	Undergoing certification; scheduled for ISS in late summer or fall 2017.
3005	SGT	No	Investigating ground water bladder leak and on-orbit performance.
3006	Onboard ISS	Yes	n/a
3007	n/a	No	Lost in Space Shuttle Challenger explosion.
3008	Onboard ISS	Yes	n/a
3009	UTAS	No	PLSS Fleet Leader and planned first reflight of a Maximized EMU Ground Activity certified unit (certification in process).
3010	Onboard ISS	Yes	n/a
3011	SGT	No	Being prepped to fulfill role as a Space Station Airlock Test Article unit. Will also be prepped for launch on need.
3012	n/a	No	Lost in Space Shuttle Challenger explosion.
3013	SGT	No	Currently in ground chamber use only.
3014	n/a	No	Lost in Space Shuttle Columbia Accident.
3015	UTAS	No	Disassembled due to water contamination experienced during EVA 18.
3016	n/a	No	Lost in Space Shuttle Columbia Accident.
3017	n/a	No	Lost in SpaceX-7 cargo mission mishap.
3018	SGT	No	Currently in ground chamber use only.

Source: NASA OIG analysis of EVA Office information.

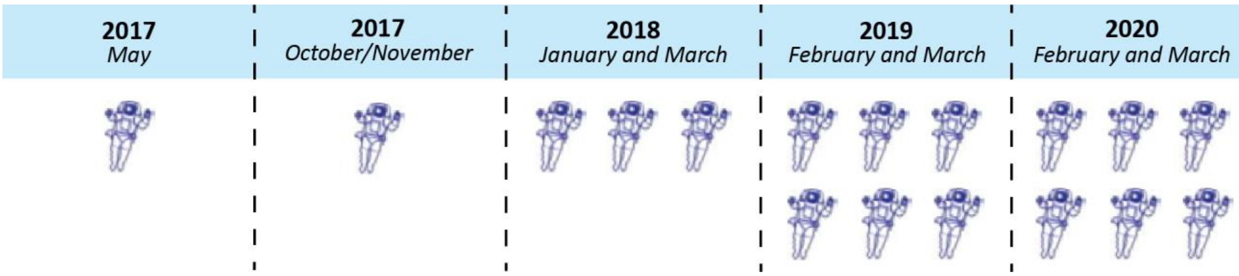
Note: Stinger Ghaffarian Technologies (SGT) and United Technologies Aerospace Systems (UTAS).

[42] The most recent loss occurred during a launch mishap of a Space Exploration Technologies Corporation (SpaceX) commercial cargo mission in June 2015.

[43] Because the associated technology is dated, the exact cost to rebuild is unknown. Estimates range as high as $250 million per unit.

NASA is planning to conduct 17 EVAs between May 2017 and March 2020: 1 in May 2017 for ISS maintenance, 1 in October or November 2017 for ISS maintenance, 1 in January 2018 to install the International Docking Adapter, and 2 in March 2018 and 6 in both 2019 and 2020 for battery replacement (see Figure 5).[44]

Figure 5: Planned ISS EVAs from May 2017 through March 2020



Source: NASA OIG analysis of EVA Office information.

In addition to these planned EVAs, the ISS Program has identified 13 "single fault tolerant systems" on the ISS – that is, systems that become inoperable after two failures – that if threatened would require a contingency EVA to prevent evacuation and potential loss of the Station.[45] For example, in December 2013, an issue with an Ammonia Pump Module resulted in the loss of one of two external cooling loops, which in turn required powering down ISS systems. Contingency EVAs were conducted on December 21, 2013, and December 24, 2013, to replace the failed module. At the time of these EVAs, all scheduled EVAs had been placed on hold due to the EVA 23 mishap – a situation that further emphasizes the critical role the EMU plays in sustaining the ISS.

[44] The International Docking Adapter will provide a port for docking commercial spacecraft at the ISS. It is designed so spacecraft systems can automatically rendezvous and dock with the Station without input from astronauts. The adapter also represents the first on-orbit element built to standardized docking measurements used by all spacecraft builders.

[45] These 13 single fault tolerant systems are called "Critical Contingency EVAs" (formerly known as the "Big 13") and consist of (1) the External Thermal Control System Pump Module used in the Climate Control System, (2) the Flex Hose Rotary Coupler that transfers liquid ammonia, (3) the Interface Heat Exchanger used to transfer heat, (4) the Solar Array Wing Bearing Motor Race Ring Module used to position a solar panel, (5) the Solar Array Wing Electronic Control Unit that controls solar panel position, (6) the Ammonia Tank Assembly that stores ammonia, (7) the Nitrogen Tank Assembly that provides a high-pressure gaseous nitrogen supply, (8) the Main Bus Switching Unit that serves as the distribution hub for the electrical power system, (9) the External Multiplexer/Demultiplexer that routes incoming and outgoing data, (10) the Direct Current to Direct Current Converter Unit that converts primary power voltage to secondary power voltage, (11) the External Remote Power Control Modules that distribute secondary power, (12) Ammonia Leak Isolation and Recovery, and (13) the Loss of Module due to Micrometeoroid Orbital Debris Penetration.

ADVANCED SPACE SUIT PROJECT STILL EARLY IN DEVELOPMENT

Since 2007, NASA has spent almost $200 million on three spacesuit development efforts – CSSS ($135.6 million), AES's Advanced Space Suit Project ($51.6 million), and OCSS ($12 million). Despite this investment, the Agency remains years away from having a flight-ready spacesuit capable of replacing the EMU or suitable for EVA use on future exploration missions. The lack of a formal plan and specific destinations for future missions has complicated spacesuit development since different missions require different designs. Moreover, the Agency has reduced the funding dedicated to spacesuit development in favor of other priorities such as an in-space habitat. Given the current development schedule, there is significant risk a next-generation prototype will not be sufficiently mature in time for testing on the ISS prior to the Station's planned 2024 retirement. We also question NASA's decision to continue to fund the CSSS after cancellation of the Constellation Program and a recommendation from Johnson leadership to terminate the contract. Finally, little schedule margin exists between delivery of the OCSS in March 2021 and NASA's internal launch date for the first crewed Orion mission in August 2021.[46]

Spacesuit Development Affected by Lack of Requirements, Reduced Funding, and Investment Choices

Development of NASA's next-generation spacesuit has been affected by three interrelated factors. First, NASA's future exploration mission destinations have not yet been formalized, which has complicated the task of designing a suit to meet the Agency's requirements. Second, funding limitations and a recent change in scope have impacted the Advanced Space Suit Project. Third, rather than concentrating its investment on developing Advanced Space Suit Project technology, NASA continued to fund the CSSS contract for more than 5 years after cancellation of the Constellation Program.

Future Human Exploration Missions Undetermined

Historically, NASA has tied spacesuit development to a specific human exploration program. For example, the Apollo Program developed spacesuits for exploring the surface of the Moon and the Space Shuttle Program developed the EMU for microgravity EVAs. However, NASA is still in the process of formulating a long-term mission architecture for its Journey to Mars and has not yet specifically identified where astronauts will go or the missions they will perform. This has hindered development of next-generation technology because without specific mission criteria, engineers must make assumptions about system requirements for future missions. For example, spacesuit requirements vary for EVAs in cislunar space, on Mars, or on the Martian moon Phobos, as each destination has different temperatures, radiation levels, pressures, mobility requirements, and exposure to dust and debris.

[46] The Acting Administrator announced in February 2017 that he had directed Agency spaceflight officials to study the feasibility of adding crew to Exploration Mission-1, scheduled for launch in late 2018.

In lieu of specific mission requirements, NASA assembled experts to create a list of requirements that would provide guidance regarding desired upgrades over current EMU functionality based on expected environments and lessons learned from using the current suits on the ISS. This list attempts to identify capabilities needed for future missions operating in microgravity and on planetary bodies. However, NASA is still in the process of evolving this list, as several key PGS requirements have not yet been specified to the level necessary for exploration missions. These requirements include a 100-EVA life cycle, dust and dirt tolerance, suited mobility for partial-gravity environments, overall fit, and micrometeoroid or other impact protection. In addition, NASA has not invested in the testing required to allow for accurate and repeatable requirements verification.

Funding Issues and Revised Project Scope

In FY 2016, competing funding priorities led AES to fund the Advanced Space Suit Project for only the first 6 months of the fiscal year.[47] Following this decision, Human Exploration and Operations Mission Directorate managers consolidated all development efforts under the EVA Office. Subsequently, the EVA Office and Advanced Space Suit Project approached the ISS Program for funding for the remainder of FY 2016 and for 2017; the ISS Program provided an additional $4.5 million in funding in FY 2016.[48] As of April 2017, ISS Program officials said they expect to spend $5 million in both FYs 2017 and 2018 for technology development related to Advanced Space Suit Project components.[49] Funding for the Project beyond FY 2018 is uncertain.

In addition to the funding issues, the focus of the Advanced Space Suit Project changed from production of an exploration spacesuit prototype for a single flight demonstration on the ISS to development of technologies that facilitate acquisition of an ISS EMU replacement using Advanced Space Suit Project exploration EVA technology. The Project plans to do this through three spacesuit iterations: the xEMU Lite for use on the ISS, the xEMU for use in cislunar space, and the mEMU for use on Mars (see Figure 6).

[47] AES is developing six technology elements for human exploration: (1) habitat systems that allow crew to live and work in space, (2) crew mobility systems that enable crew to conduct "hands on" exploration, (3) vehicle systems needed for in-space propulsion and landers, (4) foundational systems to enable more efficient mission and ground operations, (5) robotic precursor activities to provide data for analyzing the feasibility of potential destinations for human missions, and (6) strategic operations, integration, and studies for deep space human spaceflight architecture and strategic planning.

[48] Of the funding provided by the ISS Program, $1.5 million was not provided until the fourth quarter of FY 2016, impacting the Advanced Space Suit Project officials' ability to plan for the use of this funding.

[49] Apart from the $10 million the ISS Program is providing to support advanced spacesuit development, the Program is supplying another $4.7 million in FYs 2017 and 2018 to build and test on the ISS an exploration class spacesuit thermal control system. In addition, the Program provided $500,000 in FY 2017 for controller development and testing of a CSSS system.

Figure 6: Future Spacesuit Hardware Configurations

Source: NASA OIG analysis of Human Exploration and Operations Mission Directorate information.

Note: "Lite" denotes a subsystem in which some noncritical technology was deferred to a later configuration. "xINFO" denotes noncritical avionics that are part of the informatics subsystem.

The xEMU Lite would include an advanced PLSS and PGS Hard Upper Torso. The xEMU builds on the PLSS and PGS technologies in the xEMU Lite and features advanced power, avionics, and software subsystems. The mEMU will likely not be finalized for many years, but could include some of the technologies featured in the xEMU Lite and xEMU. The EVA Office plans to develop PLSS technology to a level equivalent to a Preliminary Design Review – which is usually associated with Technology Readiness Level 6 – and possibly issue a procurement by 2019 for an EMU replacement, a scenario under which a new spacesuit could be delivered to the ISS in 2023 for testing.[50]

NASA intended to test the Z-2 PGS prototype in both a vacuum chamber and Johnson's Neutral Buoyancy Laboratory. Although the Agency conducted tests in the Neutral Buoyancy Laboratory between September 2016 and April 2017, officials told us schedule constraints and uncertain funding resulted in a decision to forgo the planned thermal vacuum chamber testing. Moreover, NASA's phased approach will result in deferring development of a number of technologies to the xEMU and mEMU phases that would have provided additional capabilities over the current EMU and xEMU Lite, potentially enabling safer, more efficient EVAs (see Table 4). Many of the technologies being deferred are currently at low Technology Readiness Levels and require development before they can be relied upon during actual missions.

[50] Technology Readiness Levels are a metric used by NASA to assess the maturity level of a specific technology. Technology Readiness Levels range from 1 (lowest) to 9 (highest). NASA policy states that reaching a Technology Readiness Level 6 – which indicates that the representative prototype of the technology has been demonstrated in a relevant environment – by the Preliminary Design Review is the level of maturity needed to minimize risks for space systems entering product development. However, Advanced Space Suit Project officials stated that not all PLSS technology would be at a Technology Readiness Level of 6 by 2019.

Table 4: Spacesuit Technology Deferred Due to xEMU Lite Plan

Capability	xEMU Lite Technology Development Plan	Current Technology Readiness Level
Modular/Orbital Replacement Unit Design	✓	2
3,000 Pounds Per Square Inch Rechargeable Primary/Secondary Oxygen	✓	4
Amine Carbon Dioxide Removal System	✓	4
Advanced Pump Technology	✓	4
Advanced Fan Technology	✓	4
1 Hour Emergency Return Capability	✓	4
Enhanced Upper Mobility	✓	4
Rear Entry Ingress/Egress	✓	4
Reconfigurable High Speed Data	Deferred	4
High-Definition Video and Lights	Deferred	4
Informatics Display and Controls	Deferred	2
Integrated Communication System	Deferred	4
Automated Suit Checkout	Deferred	2
4.3 to 8.2 Pounds Per Square Inch Variable Suit Pressure	Deferred	4
Planetary Mobility	Deferred	4

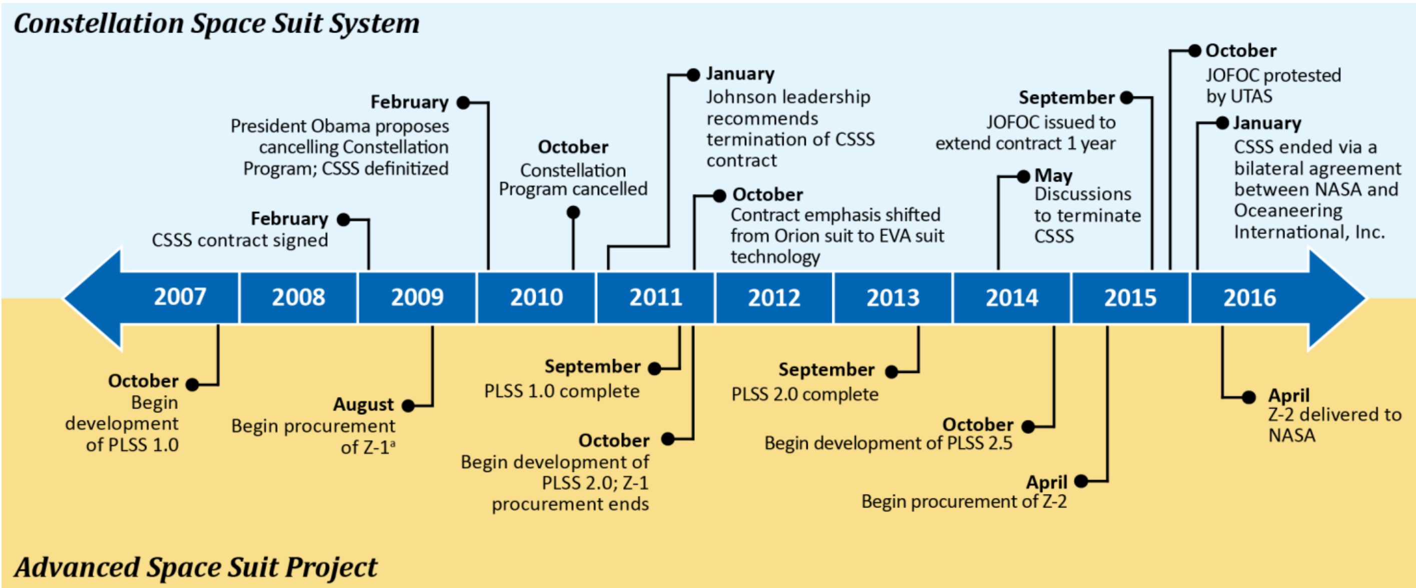
Source: NASA.

Continued Funding of the CSSS

The CSSS contract was originally intended to provide NASA with spacesuits appropriate for Constellation Program mission requirements. After the Program's cancellation in October 2010, Johnson leadership recommended terminating the contract in favor of in-house development efforts by NASA civil servants, estimating that NASA could save $5 million in FY 2011 alone. However, Human Exploration and Operations Mission Directorate leadership chose to continue to fund part of the contract to carry on industry development of EVA technologies, and in October 2011 NASA redirected efforts under CSSS to focus on technology development, such as cooling system components and a prototype PGS. For each subsequent year, the EVA Office, in conjunction with the ISS Program and Human Exploration and Operations Mission Directorate management, determined the budget and provided direction for continued use of the contract for technology development and EMU risk reduction. Ultimately, NASA ended the contract through a bilateral agreement with the contractor in January 2016. NASA spent $80.8 million on the CSSS contract between FY 2011 and FY 2016.[51] As noted earlier, throughout this period NASA was also funding AES's Advanced Space Suit Project development efforts (see Figure 7).

[51] Details regarding our calculation of these funds can be found in Appendix D.

Figure 7: Concurrent CSSS Contract and Advanced Space Suit Project Technology Development



Source: NASA OIG analysis of Human Exploration and Operations Mission Directorate information.

Note: Justification for Other than Full and Open Competition (JOFOC).

[a] The Z-1 upper torso assembly was procured under the CSSS contract and the lower torso was developed by ILC Dover under NASA's Exploration Technology Development Program, the predecessor to AES's Advanced Space Suit Project technology development efforts.

We question the Agency's decision to continue to fund the CSSS contract after Johnson leadership recommended its termination in early 2011. First, we believe NASA was adequately engaging the spacesuit-developer industry through the Advanced Space Suit Project, which involved major procurements with 13 contractors between FY 2012 and FY 2016.[52] Moreover, the CSSS and Advanced Space Suit Project efforts shared several contractors and primary sub-contractors who specialize in PGS or PLSS component development, providing NASA with ample options to seek development of spacesuit systems. Second, to the extent the Agency was concerned about preserving the capabilities of CSSS prime contractor Oceaneering International, Inc. we believe the concern was unnecessary because this was the first time Oceaneering had served as a prime contractor on a NASA spacesuit development project and the existing contractor base had provided sufficient capability for the Agency in the past.

We also base our conclusion on the deliverables NASA received under the contract. Specifically, many of the systems the contractor developed were redundant to Advanced Space Suit Project systems – meaning that major components in the PLSS vent and water loops were being developed both by the Project and the contractor. Moreover, many of the contractor's designs were at lower Technology Readiness Levels than the hardware the Project developed. For example, one study found the Rapid Cycle Amine swingbed used in the Advanced Space Suit Project design is "far more advanced" than the CSSS concept.[53] NASA has incorporated several of the contract deliverables into the Project's EVA systems – such as a controller for the thermal loop and an integrated communications system for the Z-2 suit – which was a benefit to the Advanced Space Suit Project because the funds did not come from

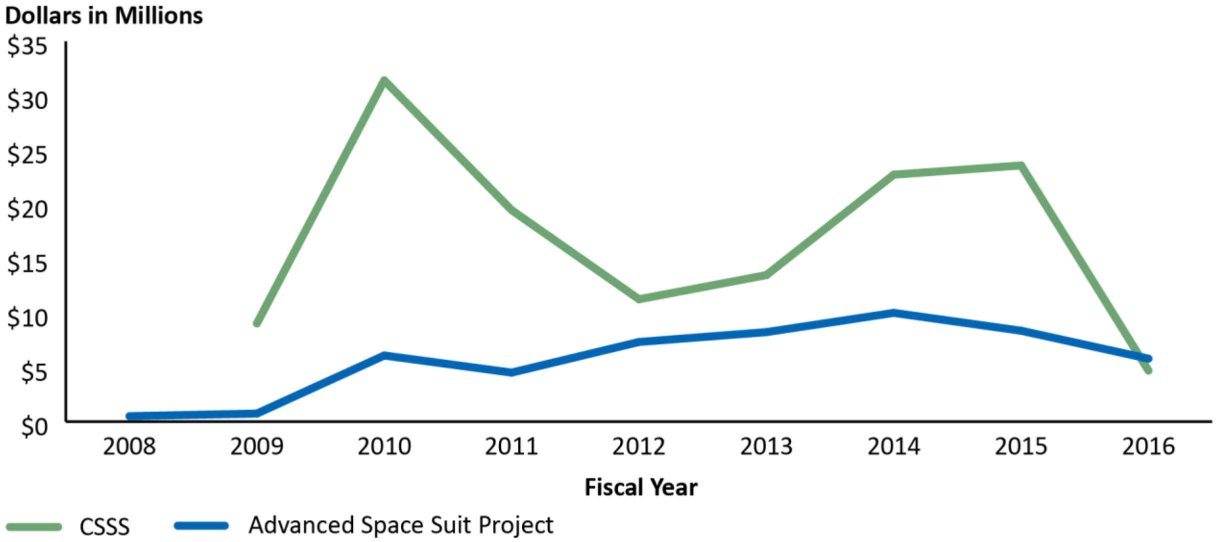
[52] A "major procurement" is defined as one in which a contractor receives more than $100,000 in a fiscal year.

[53] The Rapid Cycle Amine swingbed is part of the PLSS carbon dioxide removal and humidity control system.

the Project's limited spacesuit technology development budget. Nonetheless, the total value of these contributions is less than $9 million out of the $80.8 million spent on the CSSS from FY 2011 through FY 2016.[54] Furthermore, we found disagreement among officials within the Human Exploration and Operations Mission Directorate about the degree to which CSSS deliverables will be used in the next-generation spacesuit design being considered for testing on the ISS.[55]

As shown in Figure 8, NASA spent more on the CSSS contract between FY 2009 and FY 2016 than on the Advanced Space Suit Project.

Figure 8: CSSS Contract Costs Versus Advanced Space Suit Project Costs



Source: NASA OIG presentation of Agency information.

Given the Advanced Space Suit Project's engagement of the spacesuit developer industry, the lack of clear contributions of CSSS deliverables to NASA's development of a next-generation spacesuit, and the amount of money spent – almost three times as much in total on CSSS than on the Advanced Space Suit Project – we question the Agency's decision to continue to fund the contract after Johnson leadership recommended its termination and the associated expenditure of $80.8 million between FY 2011 and FY 2016 (see Appendix D).

Tight Timeline for Testing Next-Generation Spacesuit on the ISS if Station is Retired in 2024

There is a significant risk that a next-generation spacesuit prototype will not be produced in time for testing on the ISS before the Station's planned retirement in 2024. Although NASA is moving toward procurement of a flight-ready article for testing, schedule margins do not allow for much, if any, delay in delivery. Under the xEMU Lite plan, the Agency aims to advance technologies to a level equivalent to a

54 This value is based on prime contractor estimates of labor and non-labor costs (including sub-contractors) plus award fees. The estimate does not include general and administrative or overhead costs.

55 In addition, Agency officials stated that other NASA programs and projects may find additional CSSS deliverables of use in the future.

Preliminary Design Review of the new PLSS in FY 2018 and begin procurement by FY 2019 with the hope of delivery of the test article to the ISS by 2023. This schedule leaves only one year for testing before the Station's planned 2024 retirement. Any delay in development or production would further erode the limited time available for testing. Of course, extending ISS operations beyond 2024 would alleviate this schedule pressure.

If the new PLSS and PGS Hard Upper Torso are not delivered to NASA with sufficient time for testing, the Agency would either have to find a platform other than the ISS for microgravity testing or procure spacesuits that rely on technology that has not been tested in its intended environment. Numerous NASA officials emphasized the criticality of testing the technology on the ISS, which provides the opportunity for testing in both vacuum and microgravity environments that cannot be fully replicated on Earth. Past experience with the EMU illustrates the importance of this type of testing, as fluid systems and other components of a spacesuit's life support system behave differently in microgravity than during Earth-based testing. For example, Earth-based testing of the EMU resulted in NASA's belief that if a significant amount of water entered the vent loop, the fan pump separator would likely stall and the water would not pose a hazard to the astronaut. However, as the EVA 23 incident demonstrated, that is not what happened in the microgravity space environment. Accordingly, if NASA procures a next-generation spacesuit without ISS testing, there is an increased risk astronauts will experience technical issues during exploration operations that could impact mission success and endanger their health. Further complicating matters, these missions will be conducted beyond low Earth orbit where there will be fewer opportunities for resupply and replacement of spacesuit components if issues arise. NASA officials told us that alternate testing platforms like civil or commercial missions to low Earth orbit have not been discussed in detail, and that in any event, such platforms would be inferior to the ISS for long-duration testing.

Availability of OCSS for Crewed Launch of Orion in 2021

NASA must also finish development and production of the OCSS in time for a 2021 Orion launch. As noted in our September 2016 report on the Orion Program, NASA is working toward an internal launch date of August 2021 for the first crewed Orion mission (Exploration Mission-2), significantly earlier than the Agency's external launch commitment date of April 2023.[56] The OCSS suits the Exploration Mission-2 crew will use are currently scheduled to be delivered to NASA in March 2021 – 5 months before the internal launch date. The Orion Program is currently fully funding OCSS development efforts and development remains on schedule. However, NASA has little schedule margin to absorb any issues related to funding, development, or production delays to meet the 2021 date. There is, however, adequate schedule margin to meet the later launch date of April 2023.

[56] NASA OIG, "NASA's Management of the Orion Multi-Purpose Crew Vehicle Program" (September 6, 2016, IG-16-029).

CONCLUSION

The lives of NASA's astronauts depend on spacesuits that enable them to operate safely in extreme environments. As the EMU ages, NASA must deal with a dwindling number of flight-ready spacesuits and with mitigating risks related to their design and maintenance. Given these issues, NASA will be challenged to continue to support the EVA needs of the ISS with its current fleet of EMUs through 2024 – a challenge that will only increase if Station operations are extended to 2028. Moreover, NASA is developing a new spacesuit for future exploration missions, and project officials say testing the new design on the ISS is critical. However, a flight-ready spacesuit will not be available for testing for several years, leaving little margin for delays in the production schedule if NASA retires the ISS in 2024 as currently planned.

RECOMMENDATIONS, MANAGEMENT'S RESPONSE, AND OUR EVALUATION

To maintain the efficacy of the EMU currently used aboard the ISS and ensure the successful development of a next-generation spacesuit, we made the following recommendations to the Associate Administrator for the Human Exploration and Operations Mission Directorate:

1. Develop and implement a formal plan for design, production, and testing of the next-generation EVA spacesuits in accordance with the exploration goals of the Agency, crew needs, and the planned retirement of the ISS in 2024. This plan should specify the technology to be tested on the ISS and any risk mitigation procedures for deferred development of exploration EVA technologies.
2. Conduct a trade study comparing the cost of maintaining the current EMU spacesuit and developing and testing a next-generation spacesuit.
3. Apply lessons learned from operations of existing EVA and launch, entry, and abort spacesuit systems to the design of future exploration spacesuit systems to ensure mitigation of non-life-threatening health risks or other injuries that could impair mission objectives.

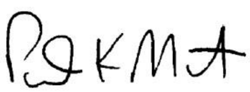
We provided a draft of this report to NASA management for review and they concurred with our three recommendations and described corrective actions the Agency plans to take. We consider management's comments responsive; therefore, the recommendations are resolved and will be closed upon verification and completion of the proposed corrective actions.

In addition, NASA management noted that while the report is a fair assessment of the current state of EVA systems, they believe we are overly critical of the data and products supplied under the CSSS contract, asserting that information and hardware from CSSS have directly impacted current and future EVA technology development efforts. However, as noted in our report, the total value of CSSS hardware contributions to the Advanced Space Suit Project design under consideration for testing on the ISS is less than $9 million out of the $80.8 million spent on the CSSS from FY 2011 through FY 2016. In addition, we found disagreement among officials within Human Exploration and Operations Mission Directorate about the degree to which many of the CSSS deliverables will ultimately be used. As such, we continue to believe that continuation of this contract did not serve the best interests of the Agency's spacesuit technology development efforts.

The full text of the Agency response is reproduced in Appendix E. Management's technical comments have also been incorporated throughout the report, as appropriate.

Major contributors to this report include, Ridge Bowman, Space Operations Director; Letisha Antone, Project Manager; David Balajthy; Shari Bergstein; Cedric Campbell; Thomas Dodd; and Alyssa Sieffert. Sarah McGrath provided editorial and graphic assistance.

If you have questions about this report or wish to comment on the quality or usefulness of this report, contact Laurence Hawkins, Audit Operations and Quality Assurance Director, at 202-358-1543 or laurence.b.hawkins@nasa.gov.



Paul K. Martin
Inspector General

APPENDIX A: SCOPE AND METHODOLOGY

We performed this audit from June 2016 through April 2017 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Our overall audit objective was to assess NASA's management of the EMUs for use on the ISS, and NASA's development of a next-generation spacesuit for future deep space applications. Specifically, we determined whether NASA has identified and properly mitigated risks of the current EMUs and to what extent NASA is meeting cost, schedule, and performance goals in the development of next-generation spacesuits. Our review was conducted at Johnson and NASA Headquarters.

To conduct a comprehensive review of the EMU mishaps, corrective actions, and remaining risks to astronauts, we reviewed the EVA 23 Mishap Investigation Board Report which included 49 recommendations to improve EVA safety. We also interviewed members of the Mishap Investigation Team and the ISS EVA Recovery Team, and reviewed the EVA readiness review that was performed after EVA 35 to determine whether nominal EVAs could continue after early termination due to water in the helmet. In addition, we reviewed the ISS Problem Analysis Reporting Tool database, which is used to track incidents with the EMU; the Anomaly Reporting database, which is used to report any anomaly that occurs on-orbit; and the Single Application Resource for Aerospace Hardware database, which is used to track information for suit refurbishment and maintenance. We also reviewed EVA risk summaries outlining the top EVA risks as determined by the EVA Office and other documents deemed significant to our audit objectives.

To assess the negative health effects of EMU use, we interviewed NASA's Chief Health and Medical Officer, the Supervisory Medical Officer at Johnson, and current and former astronauts. Additional documents we reviewed included the EVA 23 Mishap Investigation Board Report, Decompression Risk Summary, Flight Surgeon presentations regarding current health risks, Volumes 1 and 2 of NASA's Space Flight Human System Standards, and the Human Integration Design Handbook.

To assess the management of ISS EVA activities, certification cycles, and EMU refurbishing, we reviewed the Assured EMU Availability Plan and the Maximized EMU Ground Activity Certification Program. We conducted interviews of EVA Office personnel and reviewed the EMU certification history. Moreover, additional documents we reviewed included the records of EMU life waivers, the Independent Review out-brief of the EMU 6-year maintenance interval, and Single Application Resource for Aerospace Hardware database records containing EMU refurbishment and maintenance information.

To assess NASA's spacesuit studies, analyses, and planning for future spacesuits, we reviewed the Advanced EVA Development Plan, which describes the development of next-generation spacesuits from FY 2016 through FY 2023. We also reviewed the FY 2016 through FY 2017 PLSS Lite Tactical Plan, which describes a potential tactical EVA development plan for an EMU replacement PLSS. Finally, we interviewed officials from the AES Division and the Orion Program office.

To assess progress in developing new spacesuits, we reviewed a series of documents, including the Integrated EVA Development Plan containing tactical and strategic EVA development activities that support ISS and future advanced EVA needs for exploration destinations to the Moon or Mars. We also interviewed AES personnel responsible for development of the new spacesuits.

To analyze the management strategy and funding for developing new spacesuits, we analyzed the cost, schedule, and performance data for the CSSS contract and the Advanced Space Suit Project. We also reviewed the CSSS Advanced Extravehicular Mobility Unit Technology assessment reports; documentation from the Orion Program notifying the CSSS Project that Orion would not require a launch, entry, and abort spacesuit to be developed, produced, or sustained under the CSSS contract; and the bilateral agreement between NASA and Oceaneering International, Inc. ending the CSSS contract. In addition, we spoke with individuals from the AES Division and CSSS contracting officials.

Use of Computer-Processed Data

We relied on computer-processed data such as queries produced from the Anomaly Reporting, ISS Problem Analysis Reporting Tool, and Single Application Resource for Aerospace Hardware databases, and cost data obtained from Business Objects – NASA's accounting system. We corroborated information with other sources where possible and performed audit steps to validate the accuracy of a limited amount of data contained in the databases, however, the data is only as accurate as that entered by the database personnel. The accuracy of the data did not affect our conclusions.

Review of Internal Controls

We reviewed and evaluated the internal controls associated with NASA's management of the current EMUs and development of next-generation spacesuits. We reviewed appropriate policies, procedures, and regulations, and conducted interviews with responsible personnel. To facilitate internal controls, the EVA Office and the Flight Operations Directorate use panels, working groups, and investigation boards that address a myriad of EVA risks. We concluded that the internal controls were adequate.

Prior Coverage

During the last 5 years, the NASA Office of Inspector General has issued six reports of significant relevance to the subject of this report. Unrestricted reports can be accessed at https://oig.nasa.gov/audits/reports/FY17/index.html.

NASA's Plans for Human Exploration Beyond Low-Earth Orbit (IG-17-017, April 13, 2017)

NASA's Management of the Orion Multi-Purpose Crew Vehicle Program (IG-16-029, September 6, 2016)

NASA'S Efforts to Manage its Space Technology Portfolio (IG-16-008, December 15, 2015)

NASA's Efforts to Manage Health and Human Performance Risks for Space Exploration (IG-16-003, October 29, 2015)

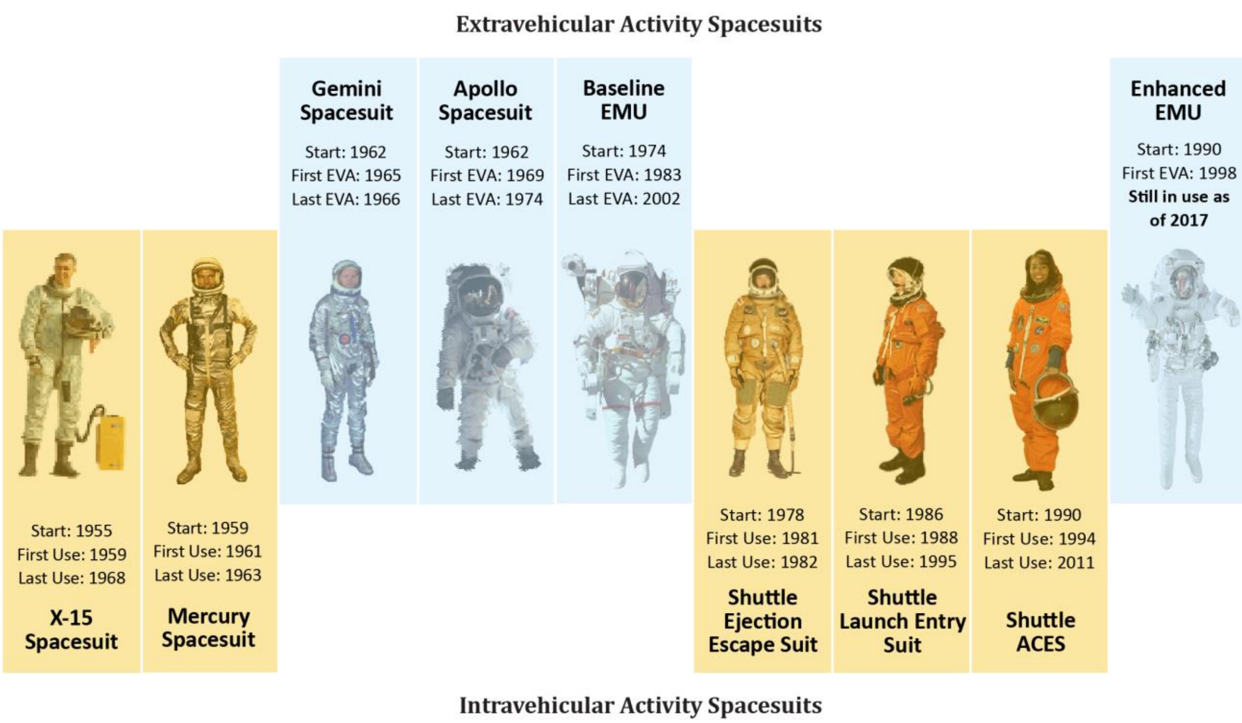
Extending the Operational Life of the International Space Station Until 2024 (IG-14-031, September 18, 2014)

NASA's Efforts to Maximize Research on the International Space Station (IG-13-019, July 8, 2013)

APPENDIX B: BRIEF HISTORY OF SPACESUITS AND EVAS

Spacesuits play a critical role in human survival and exploration outside of Earth's atmosphere. The design of a spacesuit must consider a variety of factors to protect astronauts in a range of environments, including on a spacecraft, in microgravity, and on the Lunar and Martian surfaces. Since 1959, NASA has utilized a number of different spacesuits for both extravehicular and intravehicular activities (see Figure 9).[57]

Figure 9: Extravehicular and Intravehicular Spacesuits Timeline

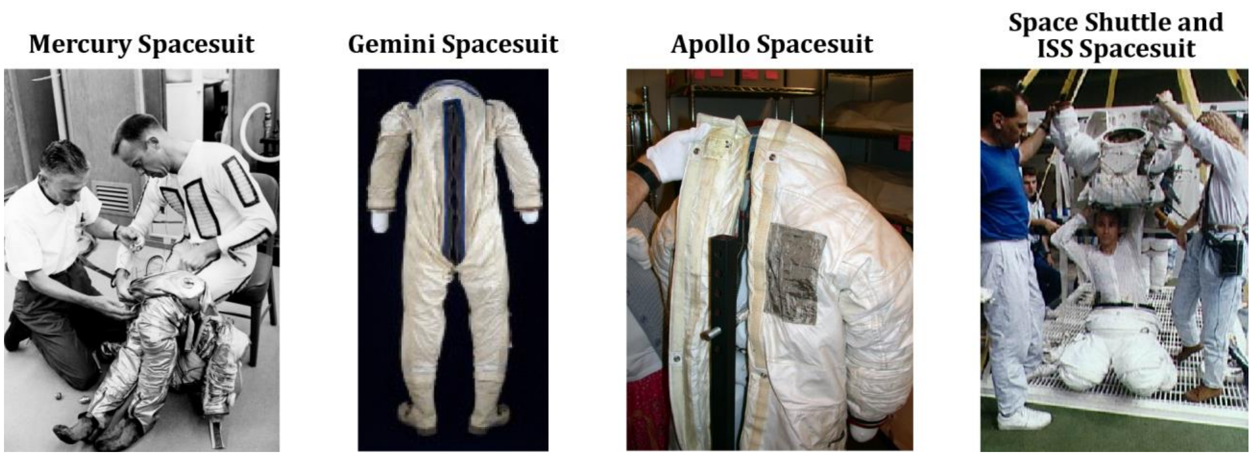


Source: NASA OIG illustration of data from NASA and Thomas, Kenneth S., and Harold J. McMann, *U. S. Spacesuits*, New York, NY: Springer New York, 2012.

[57] Intravehicular activities include any operations conducted by the crew within the vehicle. While the crew wears standard clothes during most Shuttle and ISS intravehicular activities, during launch and landing, astronauts wear specialized launch, entry, and abort spacesuits designed to protect the crew from associated hazards. However, during early NASA missions, including the X-15 program, the Mercury Program, and the Gemini Program, astronauts did not have the opportunity to change their spacesuits and had to wear those suits to conduct all intravehicular activities as well as EVAs.

Early spacesuits used for the Mercury Program between 1959 and 1963 were based on the pressure suits designed for high-altitude aircraft pilots, including the earliest pressure suit – the X-15.[58] Designed to keep pilots and astronauts in a pressurized environment during spacecraft emergencies, Mercury spacesuits contained flotation and atmosphere retention systems in the event of vehicle decompression and for intravehicular activities. However, the need for EVA capabilities led to the Gemini spacesuit in 1962, which included thermal overgarments and helmet sun visors, and provided life support through an umbilical cord as part of the G3C model.[59] In contrast with later spacesuits, the Mercury spacesuit used flexible material that allowed side-entry as compared to the thicker material used for the Gemini, Apollo, Shuttle, and ISS spacesuits. The different methods of entering the Mercury, Gemini, Apollo, and Space Shuttle and ISS spacesuits are shown in Figure 10.

Figure 10: Demonstration of Spacesuit Entry Methods



Source: NASA.

As NASA transitioned to the Apollo Program in the early 1960s, it aligned its spacesuit development with the three "blocks" of the Program. Early Block I missions utilized intravehicular activity spacesuits similar to those used on the Gemini missions and included less insulation, no arm bearings, and one pair of life support connectors. A completely different spacesuit system designed to operate with extravehicular accessories for Lunar EVAs was developed for the Block II missions. First used in 1968, this was the spacesuit used for the historic Apollo 11 mission and included a pressure suit assembly,

58 Project Mercury was the United States' first manned space program. The objectives of the Program, which made six manned flights from 1961 to 1963, were to orbit a spacecraft around Earth, investigate man's ability to function in space, and recover both man and spacecraft safely. The X-15 Program was a joint research program that NASA conducted with the U.S. Air Force, the U.S. Navy, and North American Aviation, Inc., to study hypersonic and space flight between December 1954 and October 1968. Among other topics, the X-15 Program studied the performance and physiology of 12 pilots in a single-seat monoplane as they set the world's unofficial speed and altitude records for crewed flight.

59 Later iterations of the Gemini spacesuit, such as the G4C, included an autonomous oxygen supply system backpack and astronaut maneuvering units, but these units were never flown.

PLSS, oxygen purge system for backup life support, visor assembly, EVA gloves, and Lunar overboots. The Block III missions as well as their associated spacesuit system were canceled. Variants of this spacesuit were used on Skylab and the Apollo-Soyuz Test Project.[60]

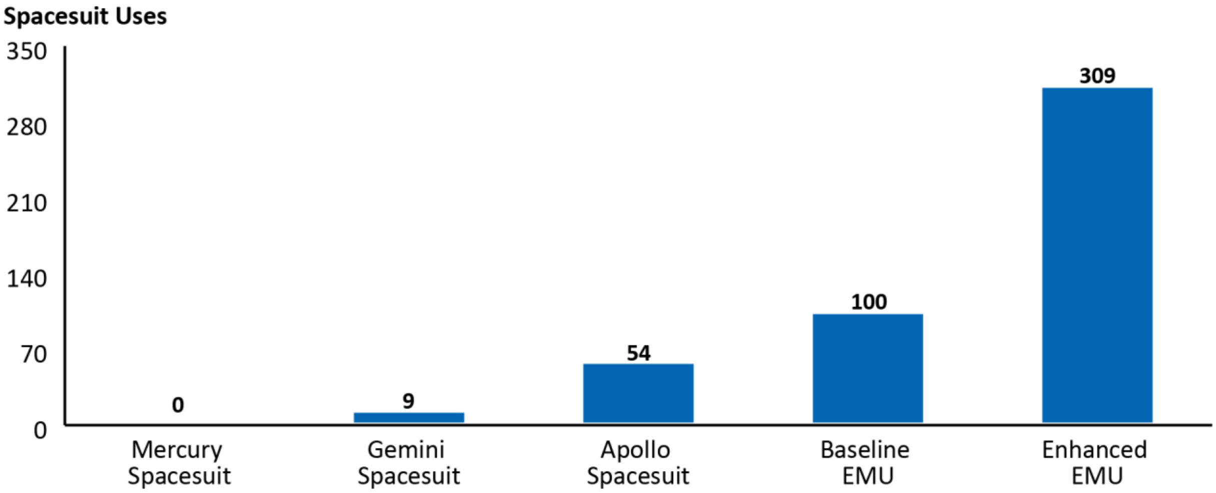
The beginning of the Space Shuttle Program required new spacesuits to meet separate launch and EVA mission requirements. The Space Shuttle Program opted to build two types of spacesuits – one for launch, entry, and intravehicular activities to be worn inside the Shuttle and another for EVAs outside the Shuttle. The Program utilized two main spacesuits for intravehicular activities: (1) the Launch Entry Suit and (2) the ACES spacesuit. The Launch Entry Suit was a partial pressure spacesuit used exclusively for intravehicular activities. This spacesuit was phased out in 1995 in favor of the ACES spacesuit, which was a full pressure system that was lighter and more comfortable. Both spacesuits utilized a parachute and flotation system in case of crew bailout. The ACES spacesuit was also used for Shuttle intravehicular activities until the end of the Space Shuttle Program in 2011.

In 1974, ILC Dover created the "baseline" EMU to meet the Space Shuttle Program's need for an EVA spacesuit. The EMU was designed for contingency scenarios in which a Space Shuttle's bay doors failed to close prior to atmospheric reentry or the rescue of a disabled orbiter became necessary. The baseline EMU was a modular spacesuit that provided pressure, thermal, and micrometeoroid protection for astronauts while performing microgravity EVAs and allowed Shuttle crew to frequently perform 7-hour EVAs without experiencing ill effects or exhaustion.

Since the assembly of the ISS began in 1998, the need for a spacesuit that could handle a drastic increase in the number of EVAs prompted modifications to the baseline EMU. The enhanced EMU is the spacesuit NASA astronauts currently use on the ISS. A key difference between Space Shuttle and ISS operations is that for the Space Shuttle, the EMU was originally developed for contingency scenarios while for the ISS the role of the EMU evolved to include deploying, capturing, and repairing satellites and enabling astronauts to assemble, repair, and maintain the ISS. Additionally, the number of EVAs required for each spacesuit and the number of years the EMU would need to operate without ground maintenance increased significantly, which required updates to the EMU such as the addition of filters in the cooling loop. See Figure 11 for a comparison of the number of EVAs performed in NASA spacesuits.

[60] America's first space station, Skylab, began as the Apollo Applications Program in 1968 with an objective to develop science-based human space missions using hardware originally developed to land astronauts on the Moon. Skylab orbited the Earth from 1973 to 1979. The Apollo-Soyuz Test Project was the first joint space effort between the United States and the Soviet Union. The mission began with the launch of the Soyuz and Apollo spacecraft, which docked in space. The next 2 days were filled with joint activities, including passing between the spacecraft airlocks, exchanging gifts, and practicing docking procedures before returning to Earth.

Figure 11: Number of Spacesuit Uses During EVAs through March 2017



Source: NASA OIG analysis based on Agency data.

Appendix C: Spacesuit Design Considerations

Depending on the mission and the targeted extraterrestrial body, various factors must be taken into account when creating a spacesuit. Within the mission parameters, spacesuit design will be influenced by vehicle design, including its size and habitation parameters, and the objectives of the mission. Based on the extraterrestrial body, spacesuits must take into account varying environments, pressures, atmospheres, temperatures, and dangers.

Vehicle Limitations

The EVA system is integrally related to the space vehicle and habitat. As such, it is imperative EVA system requirements be developed in conjunction with the vehicle requirements. Of particular interest is the determination of operating pressure, which affects the spacesuit and vehicle system design and drives the pre-breathe procedures, which has ramifications for both the operational scenarios (increased crew time and spacesuit mobility limitations) and the physiological health and safety of the crew. Other issues include overall vehicle architecture considerations, such as mass and volume, and physical interfaces.

Mission Objectives

Spacesuits must be capable of performing a full range of expected mission objectives. For example, while operating outside of the ISS does not require leg mobility, gathering geological samples on a planetary surface does, which results in different mobility requirements to achieve mission objectives. Additionally, the amount of time available for spacesuit maintenance, preparation, donning, and doffing must be consistent with the time limitations required to achieve a mission's science goals while providing sufficient time for other operations.

Environments

The gravitational and surface compositions of an environment influence the design of a spacesuit. Additionally, the environment can limit whether the spacesuit is open-loop – in which stored consumables like water and oxygen are used once by the crew and discarded – or closed-loop – in which consumables can be reutilized without being vented out of the spacesuit – based on whether there is an atmosphere on the surface. Surface environments generate a unique set of natural hazards – such as sharp rock formations, dust, and dirt – that can accelerate wear of soft goods and create fire hazards if lodged in oxygen systems. In addition, the composition of dirt and dust will create destination-specific human health hazards associated with contact and inhalation. For example, during the Apollo missions, Lunar dust made the spacesuits difficult to fit and caused abrasions.

Pressure

Earth's pressure at sea level is 14.7 pounds per square inch. The ISS also uses a pressure of 14.7 pounds per square inch; however, the EMU operates at 4.3 pounds per square inch. This lower pressure allows for more flexibility in the spacesuit. However, rapid depressurization to reach 4.3 pounds per square inch increases the risk of decompression sickness for astronauts. To prevent this, NASA uses pre-breathe procedures to slowly depressurize cabins and decrease astronauts' nitrogen content. These procedures can take 4 to 12 hours, depending on the specific protocol. Additionally, designs must consider hand mobility, which is also impacted by the spacesuit's pressure.

Respiration

Providing oxygen and removing carbon dioxide is essential and varies based on the operational environment. Flammability and long-term medical concerns pose threats to astronauts in pure oxygen environments. However, oxygen is necessary to sustain life, and high levels of gases such as carbon dioxide can lead to sickness and death. While most of the PLSS components could remain the same between the ISS and Mars, the carbon dioxide and humidity removal system requires vacuum exposure, which does not exist on Mars, requiring that systems for the removal of carbon dioxide be redesigned for planetary surfaces without vacuum.

Humidity Control

Perspiration and exhaled water must be controlled for in the spacesuit while also preventing the spacesuit environment from becoming too dry and irritating the eyes. Too much water in the spacesuit can lead to water intrusions while too little water can impact the operations of some types of carbon dioxide removal technologies and make astronauts uncomfortable.

Nutritional Provision and Waste Disposal

Astronauts spend hours in their spacesuits, which means the suit must be capable of providing food and water and control for human waste during EVAs. For example, as the Agency focuses on longer-duration human exploration goals, human waste systems for launch, entry, and abort spacesuits need to evolve past the traditional adult diaper currently in use. In October 2016, NASA engaged the public to develop new methods for disposal of human waste while wearing intravehicular spacesuits. The winner was announced in February 2017.

Thermal Control

Astronauts can be exposed to a wide range of temperatures. In space, temperatures can be as low as negative 387 degrees Fahrenheit. On the Moon, temperatures can range from negative 250 to 250 degrees Fahrenheit. Mars has a thin atmosphere, but temperatures can still range from negative 120 to 13 degrees Fahrenheit. Spacesuits must use insulation to keep astronauts safe in these extreme conditions. In addition to insulation, heat rejection capabilities are different in different environments. For example, the new water cooling device designed for use in the PLSS needs a vacuum source, and therefore must be redesigned for Mars.

Space Debris

The ISS moves at 17,500 miles per hour. Orbiting particle debris can be dangerous; therefore, astronauts performing an EVA must be adequately protected from potential punctures to the pressurized environment of the spacesuit.

APPENDIX D: QUESTIONED COSTS CALCULATION

NASA held a meeting on January 28, 2011, during which Johnson senior staff recommended to Human Exploration and Operations Mission Directorate senior management that NASA terminate the CSSS contract. The Agency's cost analysis concluded that based on the spending rate of between $750,000 and $1 million a month on the contract, the Agency would save $5 million in FY 2011 were it to terminate the contract. However, NASA did not terminate the contract at that time, but rather continued funding CSSS until it was ended through a bilateral agreement in January 2016.

As shown in Table 5, NASA spent almost $75.8 million on CSSS between FY 2012 and FY 2016. When this amount is combined with the estimated $5 million savings in FY 2011, NASA could have avoided spending almost $80.8 million.

Table 5: CSSS Expenditures By Fiscal Year

	Fiscal Year					
	2012	2013	2014	2015	2016	Total
CSSS expenditures (dollars in millions)	$11.3	$13.5	$22.7	$23.6	$4.7	**$75.8**

Source: NASA OIG analysis of NASA expenditures.

However, NASA's estimate that it would save $5 million in FY 2011 may have been conservative. As shown in Table 6, the Agency spent approximately $12.6 million from February 2011 through September 2011. We used the $5 million figure for our FY 2011 calculations because that was the information available to the Agency when the contract was recommended for termination.

Table 6: CSSS Expenditures for February Through September 2011

	2011								Total
	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	
CSSS expenditures (dollars in millions)	$1.6	$1.8	$1.5	$1.9	$1.5	$1.5	$1.5	$1.3	**$12.6**

Source: NASA OIG analysis of NASA expenditures.

We spoke with Program officials regarding the $5 million in estimated savings for FY 2011, how this amount was calculated, and whether the figure included consideration of contract costs related to Termination for Convenience of the Government. They stated this estimate was based on robust cost analyses using the monthly spending rate for the contract for FY 2011. Furthermore, officials said that there would have been little risk in financing a termination of the contract, because costs associated with termination were already funded to the contractor in an escrow account called a Potential Termination Liability allocation.

Appendix E: Management's Comments

National Aeronautics and Space Administration
Headquarters
Washington, DC 20546-0001

April 20, 2017

Reply to Attn of:

Human Exploration and Operations Mission Directorate

TO: Assistant Inspector General for Audits

FROM: Associate Administrator for Human Exploration and Operations

SUBJECT: Agency Response to OIG Draft Report, "NASA's Management and Development of Spacesuits" (A-16-014-00)

NASA appreciates the opportunity to review and comment on the Office of Inspector General (OIG) draft report entitled, "NASA's Management and Development of Spacesuits," dated March 27, 2017.

In general, the report is a fair assessment of the current state of Extravehicular Activity (EVA) systems. However, NASA believes the report is overly critical of the data and products supplied regarding the Constellation Space Suit System (CSSS) contract. During the audit, we have provided specific information on the hardware and data deliverables provided by this contract. Additionally, we provided examples of how this information and hardware have directly impacted current and future EVA technology development efforts. In some cases, the deliverables of the CSSS contract may be used to reduce risk for current International Space Station (ISS) EVA systems. We respectfully disagree that the facts presented to the OIG support that portion of the report.

In the report, the OIG makes three recommendations to the Associate Administrator for Human Exploration and Operations Mission Directorate (HEOMD) to maintain the efficacy of the Extravehicular Mobility Units (EMU) currently used aboard the ISS and ensure the successful development of a next-generation spacesuit.

Specifically, the OIG recommends that the Associate Administrator for HEOMD:

Recommendation 1: Develop and implement a formal plan for design, production, and testing of the next-generation EVA spacesuits in accordance with the exploration goals of the Agency, crew needs, and the planned retirement of the ISS in 2024. This plan should specify the technology to be tested on the ISS and any risk mitigation procedures for deferred development of exploration EVA technologies.

Management Response: Concur. HEOMD will assess all exploration goals as they affect EVA system design and requirements, crew needs, and long-term requirements for

EVA capability and will develop a plan that is consistent with the Agency's goals and objectives for exploration. As the Agency's exploration goals are evolving, NASA will take into consideration possible demonstration activities on ISS as well as future needs and technologies and risk mitigation activities for an exploration class EVA capability.

Estimated Completion Date: The Agency will have a proposed plan for implementing an EVA capability for exploration by September 30, 2017.

Recommendation 2: Conduct a trade study comparing the cost of maintaining the current EMU spacesuit and developing and testing a next-generation spacesuit.

Management Response: Concur. HEOMD will assess procurement cost estimate data for continued ISS EVA operations using the EMU, including expected upgrades: for example, the CO2 sensor, the EVA data recorder with wireless transmission, and high-definition helmet cameras. We will compare this estimate to the cost for development and testing of an advanced EVA microgravity flight system, which includes the pressure garment system, the primary life support system, and other subsystems. The trade study results will be used to support the development of the Agency plan referenced in Recommendation 1 above.

Estimated Completion Date: September 30, 2017

Recommendation 3: Apply lessons learned from operations of existing EVA and launch, entry, and abort spacesuit systems to the design of future exploration spacesuit systems to ensure mitigation of non-life-threatening health risks or other injuries that could impair mission objectives.

Management Response: Concur. NASA continually applies lessons learned not only to future developments but, also, to the ongoing ISS EVA activities. Technical and operational reviews of the ongoing lessons learned have resulted in the development of next-generation spacesuit design goals and modification to the operations and maintenance of the current ISS EMU. A top-level trace of lessons learned to exploration EVA development will be included in the plan referenced in Recommendation 1 above.

Estimated Completion Date: September 30, 2017

We have reviewed the draft report for information that should not be publicly released. As a result of this review, we have not identified any information that should not be publicly released.

Again, thank you for the opportunity to review and comment on the subject draft report. If you have any questions or require additional information regarding this response, please contact Michelle Bascoe at (202) 358-1574.

William H. Gerstenmaier

cc:
HQ/Chief, Health Medical Officer/Dr. J. Polk
HQ/ISS Director/Mr. S. Scimemi
JSC/Director/Dr. E. Ochoa
JSC/Program Manager/Mr. K. Shireman
JSC/EIS Director/Ms. V. Wyche
JSC/EVA Manager/Mr. C. Hansen

APPENDIX F: REPORT DISTRIBUTION

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House Committee on Oversight and Government Reform
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    Subcommittee on Oversight
    Subcommittee on Space

(Assignment No. A-16-014-00)