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EVA Systems Technology Gaps and Priorities 2017

Brian J. Johnson[1] and Jesse A. Buffington[2]
NASA Johnson Space Center, Houston, TX, 77059

Performance of Extra-Vehicular Activities (EVA) has been and will continue to be a critical capability for human space flight. Human exploration missions beyond LEO will require EVA capability for either contingency or nominal activities to support mission objectives and reduce mission risk. EVA systems encompass a wide array of products across pressure suits, life support systems, EVA tools and unique spacecraft interface hardware (i.e. EVA Translation Paths and EVA Worksites). In a fiscally limited environment with evolving transportation and habitation options, it is paramount that the EVA community's strategic planning and architecture integration products be reviewed and vetted for traceability between the mission needs far into the future to the known technology and knowledge gaps to the current investments across EVA systems. To ascertain EVA technology and knowledge gaps many things need to be brought together, assessed and analyzed. This includes an understanding of the destination environments, various mission concept of operations, current state of the art of EVA systems, EVA operational lessons learned, and reference advanced capabilities. A combined assessment of these inputs should result in well-defined list of gaps. This list can then be prioritized depending on the mission need dates and time scale of the technology or knowledge gap closure plan. This paper will summarize the current state of EVA related technology and knowledge gaps derived from NASA's Exploration EVA Reference Architecture and Operations Concept products. By linking these products and articulating NASA's approach to strategic development for EVA across all credible destinations an EVA could be done in, the identification of these gaps is then used to illustrate the tactical and strategic planning for the EVA technology development portfolio. Finally, this paper illustrates the various "touch points" with other human exploration risk identification areas including human health and performance.

Nomenclature

AES = Advanced Exploration Systems
ARM = Asteroid Redirect Mission
BAA = Broad Area Announcement
CTSD = Crew and Thermal Systems Division (Division within JSC Engineering Directorate)
x = prefix denoting "Exploration"
DRM = Design Reference Mission
EISD = Exploration Integration and Science Directorate (Directorate at JSC)
EMU = Extravehicular Mobility Unit
ETDD = Exploration Technology Development and Demonstration
ETDP = Exploration Technology Development Program
EVA = Extravehicular Activity
FCT = Future Capabilities Team
FOD = Flight Operations Directorate (Directorate at JSC)
HEOMD = Human Explorations and Operations Mission Directorate
HRP = Human Research Program
LEO = Low Earth Orbit

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[1] Lead, EVA Exploration Office, EVA Office, XX4.
[2] Lead, Exploration EVA Strategic Planning and Architecture Integration.

MSC = Mars Study Capability (Team)
NASA = National Aeronautics and Space Administration
OCT = Office of Chief Technologist
PGS = Pressure Garment System
PLSS = Portable Life Support System
ISS = International Space Station
RD = Requirements Document
SMT = Systems Maturation Team
SBIR = Small Business Innovative Research
SR&QA = Safety, Reliabilty, and Quality Assurance
STMD = Space Technology Mission Directorate
STTR = Small Business Technology Transfer
USOS = United States On-orbit Segment

I. Introduction

NUMEROUS architecture studies have and continue to be conducted to address human space exploration beyond Low Earth Orbit (LEO). Since 2010, most of these studies have focused on a "capability driven framework" which would eventually enable a future human mission to Mars.[1] In the last few years, this has morphed to the "Journey to Mars" campaign, in which all exploration steps NASA takes are in the context of ultimately sending humans to the red planet.[2] Current studies assume completion of programs in place such as the Orion spacecraft and Space Launch System as key elements (or capabilities) in the transportation architecture. Understandably all architecture studies must also assume development of new in-space transportation systems as well as a host of destination elements, including advanced EVA Systems. The maturing capabilities and current studies appear to be vectoring towards a phased execution approach, one step closer to a formal flight program or multiple programs. With each step NASA, Commercial Industry and our International Partners will gain valuable experience further reducing the risk of one day sending humans on a lengthy mission to Mars.

A key destination element for any human space journey is the ability to perform an Extra-vehicular Activity (EVA). As such, EVA needs, goals and objectives are part of almost every human space exploration study. After many years of responding to various studies to the relatively few destinations within the grasp of any known human spaceflight transportation architecture in the next 20-40 years, the EVA community has determined that there is a "super class" of missions that drive EVA architecture solutions. For each mission class the EVA community has become more efficient in capturing the needs, capabilities desired, operations, environments and ultimately the technology and knowledge gaps existing for these mission classes. The key mission classes for EVA design will be discussed and prioritized in a rough order of timing of need in the body of the paper. Additionally this paper outlines the most recent guidance, expectations and studies that are steering EVA technology development and overall EVA architecture maturation. This paper also provides an explanation of the currently available list of known EVA technology and knowledge gaps. Finally this paper will summarize the many space architecture touch points that will affect EVA design but are not within the direct perview of the EVA organizations. Communication across all stakeholders will be key in implementing a sustainable and robust future for EVA.

II. Program Direction and Support of EVA

EVA flight systems and development are currently guided by a reltively short list of programs and direction from NASA leadership. The current programs or "customers" supporting EVA technology development and/or risk reduction are listed below:

Programmatic Efforts with Technology or Risk Reduction Efforts Potentially Applicable to Exploration EVA System Development	
The International Space Station Program (ISS)	USOS EVA flight operations and Technology Development/Risk Reduction
The Human Research Program (HRP)	Researches fundamental human physiology, mitigates physiological risks related to or induced by EVA

Until recently EVA was supporting two other program/projects. In the spring of 2017 NASA canceled the Asteroid Redirect Mission (ARM) which included a Crewed Mission to enable EVA retrieval of asteroid samples. For this program, the EVA community was supporting the mission planning and Pre-Phase A conceptual development of "Capsule Based EVA" (using the Orion spacecraft as an EVA platform). With the demise of this program, this specific EVA capability is no longer being pursued. The second recent cancellation was the Advanced Space Suit project within the Advanced Exploration Systems (AES) program. This project which ended in mid-2016 was the culmination of a relatively long history of EVA-focused development programs. These included the Exploration Technology Development and Demonstration (ETDD) Program (2005-2010), Exploration Technology Development Program (ETDP, 2010-2011) and AES program (AES, 2012-2016). These programs have, in a serial fashion enabled a great leap forward in technology development for advanced EVA systems. Currently the ISS program has provided resources to continue maturing EVA technologies in support of current EVA risk mitigation and future exploration needs. The purpose and outcomes of these efforts will be further discussed in Section V.

In addition to supporting and delivering for current and past program requirements, the EVA community is also responsive to general exploration guidance received from NASA headquarters. Recently the NASA Human Exploration Operations Mission Directorate (HEOMD published HEOMD-001, "Human Exploration and Operations Exploration Objectives".[3] This document concisely outlines the objectives to be accomplished on each Phase of the Journey to Mars. The details of this guidance and the effect upone EVA development will be discussed in Section IV.

In addition to the above programs and direction, many other smaller programs/projects/tasks with EVA relevancy exist within HEOMD and other NASA Divisions such as the Space Technology Mission Directorate (STMD). These include Small Business Innovative Research (SBIR) contracts, Small Business Technology Transfer (STTR) contracts , Independent Research and Development (IR&D) funded projects, etc.

While the existence of such a wide variety of current and historical effort is certainly preferred over the alternative (i.e. a situation wherein there is little to no ongoing work in the field) it does raise a non-trivial set of questions:

What product does NASA use to compare, contrast and integrate across the elements of the EVA Community's gaps, risks, and unfunded work, particularly for future systems intended for use beyond Low Earth Orbit?

What product does NASA use to proactively coordinate support across the EVA Community's wide spectrum of exploration development work?

Where can one go to obtain awareness of ongoing efforts, particularly during consideration of new-start activities and proposals?

Where can one go to obtain a view of the rate of progress being made towards future EVA Systems?

Clearly these questions lead to the need for a product that speaks to the distributed nature of the EVA System across Human Spaceflight programs, concept studies and flight vehicle architectural elements. Accordingly, NASA began an extensive effort to create an annual product entitled the Exploration EVA System Development Plan (EVA SDP). This ICES paper represents a summary of the 2017 EVA SDP appropriately tailored for public release.[4]

III. EVA Community Insight

EVA is both a system and a capability. EVA development and operations encompasses the life cycle of spaceflight hardware starting from strategic planning to development to operations. Finally EVA is a core competency for the Johnson Space Center (JSC) in support of overall agency goals for human spaceflight.[5] As such JSC maintains an EVA Office to centralize EVA operations and development management, allowing multiple programs and missions to be supported via a single office. The office oversees the design, development, manufacturing, certification, and sustaining of all existing EVA hardware and develops the strategy for extending EVA capability on ISS and for future exploration misions. However a tremendous bulk of the work and effort is performed by all the various supporting organizations and entities, including industry and academia. A summary listing of the various organizations and entities that support EVA is depicted in Figure III-1.

Figure III-1

A goal of this paper is to continue to help all the supporting entities to understand where their expertise can best be enlisted to support continued safe operation of EVA. Though small in numbers, the EVA Community is broad and diverse in membership. Experts and leaders from all aspects of NASA, including Safety and Mission Assurance, Science and Technology Development, Engineering, Programmatics, Procurement, Academia and Industry work together with International Partners to make EVA successful. In doing so, the EVA Community members pursue many parallel paths:

- Continual support of the existing operating EVA System on ISS, including a robust Assured EMU Availability Program supported by ISS which works to extend the life and availability of the existing EMU fleet
- Infusion of new technologies (such as alternative CO2 Sensor designs) into the flight EMU fleet
- Coordination of flight operations, training activities and hardware exchanges with International Partners through the ISS Program
- Pursuit of a NASA Exploration EVA Suit Reference Design through the agency's Advanced EVA Development project
- Creation of Exploration EVA SE&I products including EVA Compatibility Requirements for robotic spacecraft and other supporting documentation for payload and future spacecraft development
- Support of an active and effective EVA System Maturation Team (EVA SMT)
- Yearly revisions to the Exploration EVA System Maturation Team Gap List
- Engagement of all HEO Exploration Design Reference Missions (DRM's) and concept or feasibility Study Teams including regular (often daily or weekly) interaction with:
  - The ISS Future Capabilities Team (FCT)
  - The Next Step Habitat BAA's
  - The Mars Study Capability Team (MSC)

Throughout the year, content from this plan is worked across the EVA Community through many project teams meetings, working groups and control boards. The primary method for general status and insight into progress toward plan content is through community membership and representative participation at the JSC/XX4 hosted Exploration EVA Working Group (EEWG). From the EEWG, topics may be forwarded to other venues such as the EVA Change Control Board (EVA CCB) or elsewhere as appropriate. A summary of venues and opportunities for communication and collaboration include but are not limited to the following:

EVA Community Coordination Venues (hosted by)	
Exploration EVA Working Group, EEWG (JSC-XX)	EVA Requirements Working Group, EVA RWG (JSC-XX)
EVA Physiology Working Group (JSC-SK)	EVA Science and Tools Collaboration Meeting (JSC-EC7 & JSC-XI)
EVA Technology Collaboration Workshop (JSC-XX)	Exploration EVA Suit Project All Hands (JSC-EC5)

IV. EVA Development Goals Amid Agency Priorities and Objectives

"Achieve safe, affordable, and effective EVA capabilities that enhance the human experience as we explore beyond Earth"

In 2016, the EVA Community worked to develop the Vision Statement shown above. Perhaps the highest level "goal" in and of itself, the EVA Vision Statement ties together the work being done to improve EVA operations on ISS today with near term and long term strategic goals for EVA capability:

- Goal: Reduce current EMU risk posture for ISS USOS EVAs through 2024
- Goal: Ensure ISS USOS EVA capability through at least 2028
- Goal: Posture NASA for longer term EVA capabilities

Upon initial inspection, some elements of the first two nearer-term goals may not readily seem to fit within an "exploration" context. However, closer examination connects them: Hardware changes and other risk reduction efforts being incorporated into the contemporary ISS EVA System are each at least partially considered for applicability/appropriateness for operations beyond ISS. A ready example of this is the ongoing CO2 Sensor Replacement/Upgrade project that supports the current EMU fleet, wherein the technologies being pursued are also chosen for their future compatibility with the NASA Exploration EVA System Reference Architecture. In this way, much as the modern day EMU used on ISS was "inherited" from the Space Shuttle Program, so too it is expected that much of the ISS EVA System will live into the next Program.

HEO's longer term EVA capability goals are represented in the recently baselined "Human Exploration and Operations – Exploration Objectives" document, HEO-001. HEO-001 divides exploration into Phases with definitions as excerpted from the text:

- **PHASE 0: EXPLORATION SYSTEMS TESTING ON ISS**
    - *This phase encompasses NASA's current human exploration activities aboard the International Space Station (ISS). The ISS enables exploration objectives in the Proving Ground and Earth Independent phases…*
- **PHASE 1: CISLUNAR DEMONSTRATION OF EXPLORATION SYSTEMS**
    - *This phase covers demonstration of the integrated Space Launch System (SLS) and Orion spacecraft and other exploration activities primarily occurring in cislunar space to support short duration objectives. Phase 1 culminates in the capstone demonstration of the Asteroid Redirect Crewed Mission (ARCM) in the mid-2020s.*
- **PHASE 2: CISLUNAR VALIDATION OF EXPLORATION SYSTEMS**
    - *This phase covers validation of integrated SLS, Orion, habitation, crew, and in-space transportation systems in cislunar space. Phase 2 culminates in the capstone demonstration of a*

  - *one year crewed “shakedown cruise” of a Mars transit habitation capability in the 2030 timeframe.*
- **PHASE 3+: BEYOND EARTH-MOON SYSTEM**
  - *This phase covers Earth Independent activities that build on what is learned on ISS and in cislunar space to enable human missions to the Mars vicinity, including the Martian moons, and eventually the Martian surface.*

The EVA-specific objectives in HEO-001 include:

- P0-04: Demonstrate in-space exploration class EVA technologies
- P1-13: Validate ability to conduct EVA in deep space
- P2-05: Validate capability and reliability of ECLSS to support a Mars class mission including dormancy periods.

Additionally, several other HEO-001 objectives are significantly enabled by EVA or have a strong EVA component:

- P1-20: Demonstrate crew operations with a natural space object in a low gravity environment
- P1-21: Enable science community objectives in deep space
- P2-10: Validate maintenance and repair capabilities in deep space with limited or no resupply
- P2-12 Enable science community objectives in deep space

Note that there are no Phase 3 definitions for EVA or any other human spaceflight system defined in the baseline of HEO-001. However, for the purposes of EVA’s strategic planning, the EVA Community’s products also articulate EVA System gaps, risks and architectural intent all the way to Mars Surface. This is done to ensure that, NASA’s Exploration EVA System Reference Architecture and other products are not developed without Mars surface in mind or without at least consideration of the challenges of being Mars-surface compatible. In some cases there may be known limits to available and emerging technologies that make them incompatible with Mars Surface, but in those cases they are identified early and the community works to place “scars” around them to limit the impact of “fixes”. As such issues emerge and are better characterized, work to reduce/eliminate the gaps and risks is prioritized.

V. Guiding EVA Technology Development and System Architecture

What has been guiding EVA technology development over the past 6 years? Where have the government references come from? How does NASA EVA community organize and communicate plans?

Between 2005 and 2010, NASA and EVA technology development was largely focused on lunar exploration. In the post-Constellation era (post 2010) NASA, in large part, abandoned the lunar focus and pursued several large architecture and DRM studies to assess the technical, cost and schedule attributes of sending astronauts to other destinations. These studies resulted in numerous operations concepts and EVA assessments. In parallel EVA technology development continued to progress. These were enabled by several programs previously mentioned including: ETDD, ETDP, AES and most recently the ISS program. Maintaining traceability between EVA architecture references, technology priorities and the latest recognized DRMs has not been easy. Communicating this traceability and justifying the need to invest in EVA technologies to NASA leadership and the public has likewise been extremely difficult. The following paragraphs will explain the approach methods used by the EVA community to guide technology development and system architecture. It should also be recognized, as with any long duration effort, the programs that fund the technology development have a large say in the direction that development will go. For example the ETDD program focused on component level maturation while AES Advanced Space Suit project focused on system level maturation and an eventual demonstration on ISS. Currently with ISS funding a vast majority of EVA technology development the focus is on system maturation, overall risk reduction for both future and current suit systems, and possibly some component/subsystem flight demonstrations.

Coalescing EVA Planning into Mission Classes: While reacting to the various studies and DRMs over the past 6 years the EVA community found itself re-creating analyses, requirements and assessments of needed technologies. This experienced (at times inefficiencies of recreating analyses) have convinced to the EVA community to create a “superset” of mission classes and reference schematics to support the near term missions. This superset is defined based upon a least-common-denominator approach that uses the fundamental features of the destination environments (e.g. gravity levels, atmospheric pressure, natural or engineered “surface”) to differentiate between the possible places humans could do an EVA with existing/expected Transportation System propulsion technologies.

- Micro-Gravity Engineered Surface, Thermal Vac
  - Gemini, Apollo deep-space, Skylab, Mir, Shuttle, ISS
- Micro-Gravity Natural Surface, Thermal Vac
  - Near-Earth Asteroids (direct interface), Phobos, Deimos
- Partial-Gravity Thermal Vacuum
  - Earth’s Moon
- Partial-Gravity Partial Atmosphere
  - Mars Surface

For reference, conceptual renderings of each of these may also be displayed:

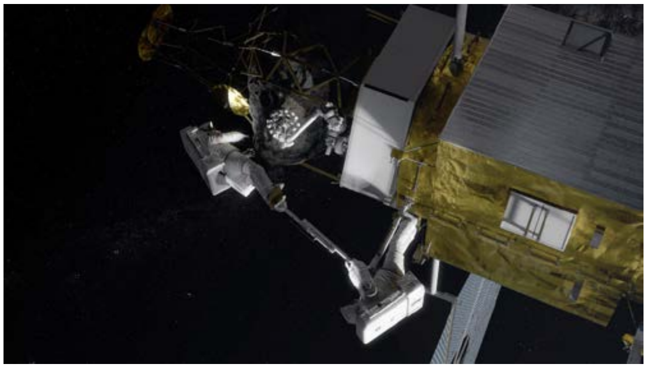


Figure V-1 Micro-Gravity Natural Surface, Thermal Vac

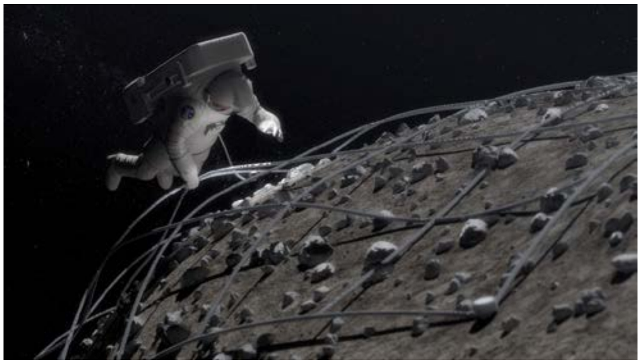


Figure V-2 Micro-Gravity, Engineered Surface, Thermal Vac

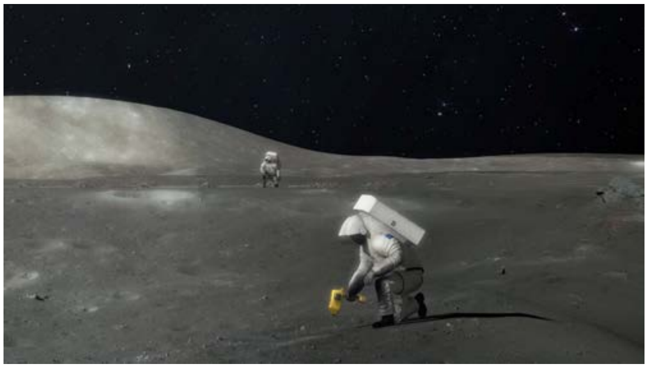


Figure V-4 Partial Gravity, Thermal Vac

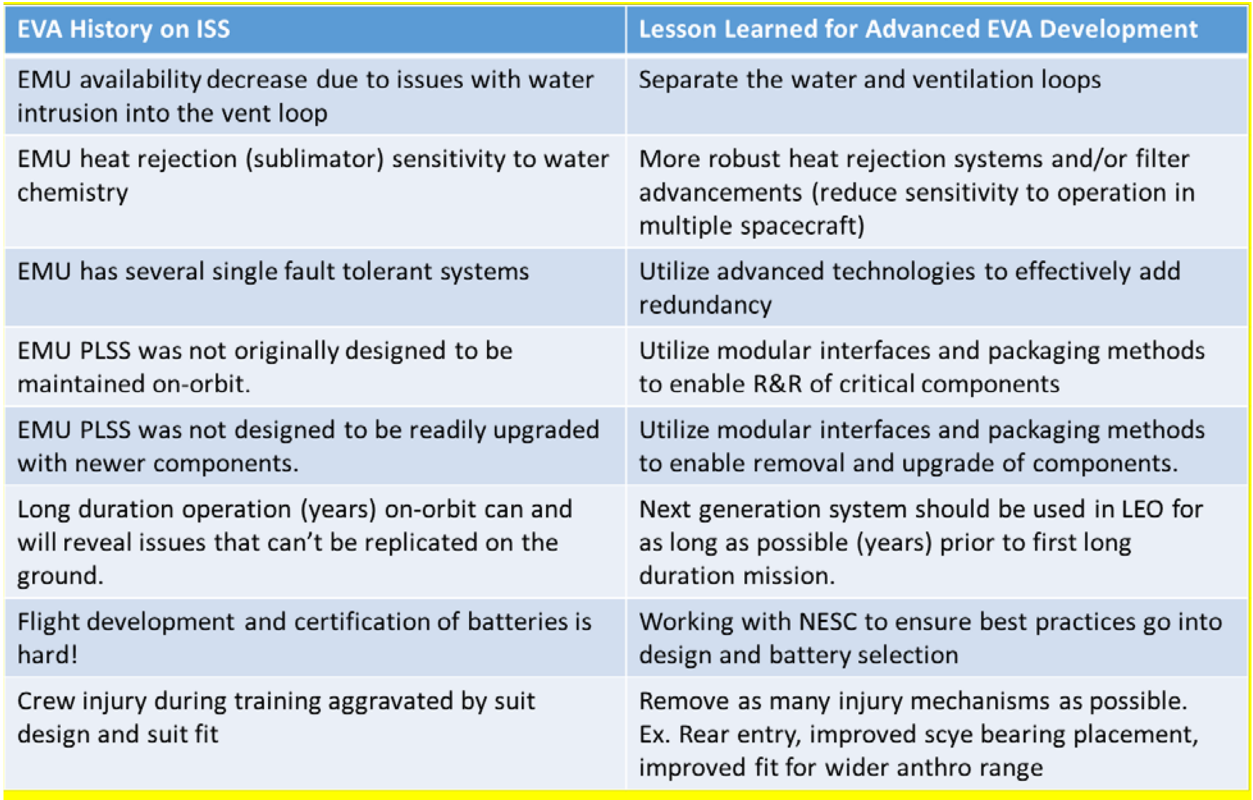
Figure V-3 Partial Gravity, Partial Atmosphere

All of EVA’s SE&I products as well as NASA’s Exploration EVA System Reference Architecture (defined in Section VI) are organized to align with the Destination Classes. For instance, instead of labelling content exclusively under “Asteroroid Study” or “HAT Moons of Mars Study”, collapsing these studies under the mission class “micro-gravity natural surface, thermal vac” will provide a benchmark ops con that is generally true regardless of whatever the study is named. This allows the system to be responsive to any portfolio of DRM studies while making progress within the EVA Community in parallel with DRM change, quickly shifting to the specifics of new DRMs as required. Technologies in the EVA portfolio can be theoretically judged by how many of the 4 mission classes that a technology can potentially support. The current Portable Life Support System (PLSS) reference schematic and technology selection, for example, incorporate technologies and architectures that can support all mission classes, with a few exceptions in the ability to support the partial pressure atmosphere and thermal extremes for Martian surface exploration. (4th mission class)

EVA Schematic and Packaging Studies: As discussed above, 2005 was an inflection point for EVA development in that this was the time many lunar based studies were initiated. Several trades and analyses were performed to ascertain the goals, requirements and technology needs for EVA. For example, in 2005/6 NASA with significant industry support performed a detailed assessment of the various life support system technologies viable for lunar mission support. This study supported by design engineers, crew, operations, and management utilized several figures of merit to down-select a technology portfolio for a complete PLSS schematic. Much of this initial schematic which was a viable solution then lives on to today as the government reference schematic, due in large part because of the fact that this schematic can effectively support several of the mission classes described earlier. Several technical papers have been written since this era communicating the maturation of the components including one paper that provides a comparison of the current schematic to the current EMU.[6]

Technology and Knowledge Gap Identification / Birth of the EVA System Maturation Team (SMT): At the human space flight architecture level, NASA HEOMD and the ISS program office have over the years sponsored several system studies. These have included Human Exploration Framework Team, Human Architecture Team, and most recently the Future Capabilities Team (FCT). To more effectively support these study teams and programs like the Advanced Exploration Program, HEOMD formulated and established SMTs. EVA currently comprises one of the several SMTs originally chartered in August of 2013. The purpose of these teams was to "fully develop a roadmap that defines the activities required to advance crucial capabilities, the means of demonstrating system performance, and the implementation planning to achieve the steps of the roadmap." (per internal letter from HEOMD to Directors). The EVA SMT and forums like the EEWG, described earlier, provide a means for coalescing, guiding and communicating the efforts between the architecture teams (from above) and the technologists in the field (from below). One of the many key accomplishments of the EVA SMT and EEWG forum is the development of a strategic EVA gaps list.[7] This list identifies the known technology and knowledge gaps in the pursuit of development of EVA hardware for all of the mission classes identified. This list is reviewed internally for the past ~2 years and is now available in a public document. Prior to this the only public source for EVA gaps was the Office of Chief Technologist (OCT) roadmaps.[8] The latest version of the maps is from 2015 and EVA technologies are primarily covered in "TA 6.2 EVA Systems" and "TA 7.3.1 EVA Mobility". The OCT maps are a good source for high level EVA architecture and technology needs and make the distinction between enhancing and enabling technology areas. However this reference is not updated but once every two years and is not going to carry the detail compared to that created by the EVA SMT.

EVA Lessons Learned: Another area of guidance for EVA development is leveraging off the vast amount of lessons learned. EVA operations have occurred for over fifty years, and in that time the community has gained an incredible amount of data that is directly applicable to development of future systems. (Table V-1 below) The EVA community has done a fairly good job at documenting and disseminating these lessons learned. In the appendix area we have provided a list of sources and online locations for research. Additionally many of the lessons learned are ported directly into the current reference requirements space and documentation associated with current systems.

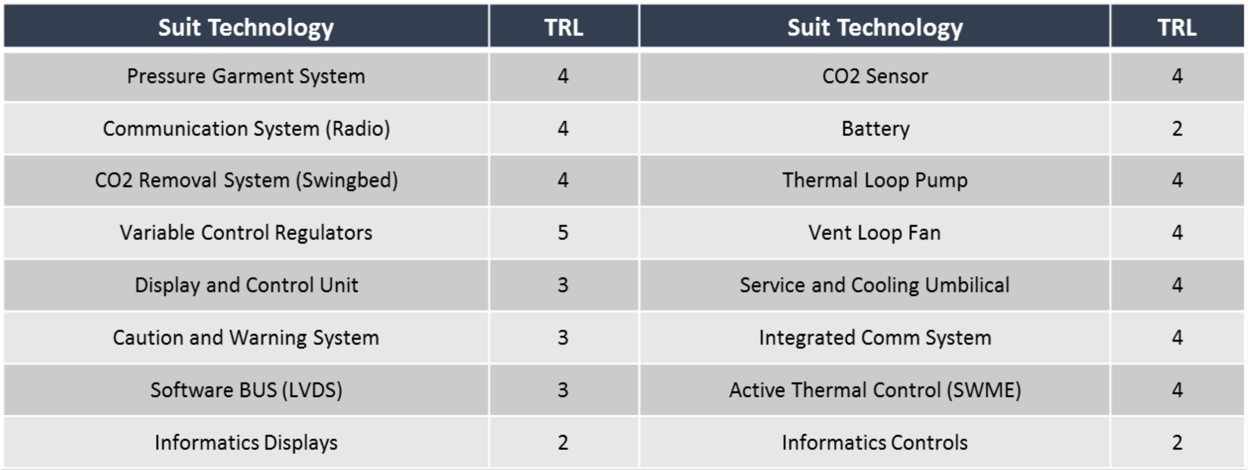


EVA History on ISS	Lesson Learned for Advanced EVA Development
EMU availability decrease due to issues with water intrusion into the vent loop	Separate the water and ventilation loops
EMU heat rejection (sublimator) sensitivity to water chemistry	More robust heat rejection systems and/or filter advancements (reduce sensitivity to operation in multiple spacecraft)
EMU has several single fault tolerant systems	Utilize advanced technologies to effectively add redundancy
EMU PLSS was not originally designed to be maintained on-orbit.	Utilize modular interfaces and packaging methods to enable R&R of critical components
EMU PLSS was not designed to be readily upgraded with newer components.	Utilize modular interfaces and packaging methods to enable removal and upgrade of components.
Long duration operation (years) on-orbit can and will reveal issues that can't be replicated on the ground.	Next generation system should be used in LEO for as long as possible (years) prior to first long duration mission.
Flight development and certification of batteries is hard!	Working with NESC to ensure best practices go into design and battery selection
Crew injury during training aggravated by suit design and suit fit	Remove as many injury mechanisms as possible. Ex. Rear entry, improved scye bearing placement, improved fit for wider anthro range

Table V-1 Examples of EVA Lessons Learned during ISS Operations

EVA Technology Validation: Another significant area guiding EVA development is of course the advancements made in EVA technology over the course of time. This is the most reactive part of guiding the path for the future of EVA but is probably the most important. Designing, building and testing technologies to discover the benefits and detriments is critical. Said another way, it is critical to advance component and system technologies to the mid TRL level prior to final mission definition and future flight acquisition, unless schedule will not allow it. For EVA there are numerous papers on the advancements made to the components and systems for suits and tools. To even try to summarize would be well beyond the scope of this paper. However some examples of the key outcomes of the expenditures made on EVA technology development include:

- Increased Size / Fit Range: Validating the ability to design pressure garments to support an expanded anthropometric range (previously thought too expensive to persue for the smaller anthropometric range)
- Packaging Validation: Packaging of all of the key PLSS technologies in a package at or less than the size of the current EMU PLSS, with additional redundancy features. (again, previously thought not possible)
- Schematic Validation: New life support technologies have been shown to effectively work together to reduce the complexity of the schematic for an advanced PLSS compared to the EMU. This should reduce cascading failure modes, reduce complexity of fault trees, improve sustainability etc.
- Component TRL maturation: Raising of TRL of Pressure Garment Systems (PGS) and PLSS component to level 4 or better. (See Table 2 below)



Suit Technology	TRL	Suit Technology	TRL
Pressure Garment System	4	CO2 Sensor	4
Communication System (Radio)	4	Battery	2
CO2 Removal System (Swingbed)	4	Thermal Loop Pump	4
Variable Control Regulators	5	Vent Loop Fan	4
Display and Control Unit	3	Service and Cooling Umbilical	4
Caution and Warning System	3	Integrated Comm System	4
Software BUS (LVDS)	3	Active Thermal Control (SWME)	4
Informatics Displays	2	Informatics Controls	2

Table V-2 Component Level -Technology Readiness Levels

All of these examples were "proven" via hi-fidelity prototype development and evaluation. In some cases this was done with parallel /independent efforts. Turning the corner and being able to reproduce these results in an affordable flight system maybe another challenge, but the technical and costs risks has been significantly reduced.

To summarize, EVA system maturation is based on a multitude of efforts. Defining mission classes, examining mission needs, data mining the historical lessons learned, identifying the state of the art for technologies, identifying technology and knowledge gaps, and finally … developing, testing and validating technologies to bridge the gaps and reduce risk for future flight system development.

VI. FY17 State of EVA Development and Tactical Plan

NASA's EVA Community has defined a suite of products that includes a conceptual "Exploration EVA System Reference Architecture" and the corresponding SE&I products that would typically be expected to support a flight project. These are best viewed through the lens of EVA Mission Classes highlighted in the previous section and the corresponding organization of HEO's Exploration DRM's. This convention is as follows:

1. Orion Crew Survival System (**OCSS**) is the LEA optimized suit being delivered to Orion
2. **EVA OCSS** adds either an EVA umbilical or xPLSS via an interface kit if a full xEMU is not available.
3. **xEMU** (xPGS + xPLSS) is the EVA suit system that supports FCT derived proving ground missions and requires minimal upgrades to enable lunar surface EVA.
    - xEMU Lite technology development effort currently funded by ISS could demonstrate some of these capabilities in Phase 0
4. **mEMU** (mPGS + mPLSS) is a Mars environment optimized EVA suit that will require new technologies.

Figure VI-1 Exploration EVA System Reference Architecture

Given these definitions and the current state of technologies, the xPLSS and xPGS are within reach. Used together or separately in some cases, these items will meet the demands of missions on the Global Exploration Roadmap (GER) from ISS to cis-lunar space, lunar surface, and the moons of Mars. For Mars Surface, the mPLSS and mEMU are needed and will require further technology development efforts.

With this architecture definition in hand, one can pursue a logical incremental capability development that minimizes the scale of the commitment needed for each new level of capability once having completed the previous. Using the Phase Definitions of the recently published HEO-001 document, this can be shown visually as follows:

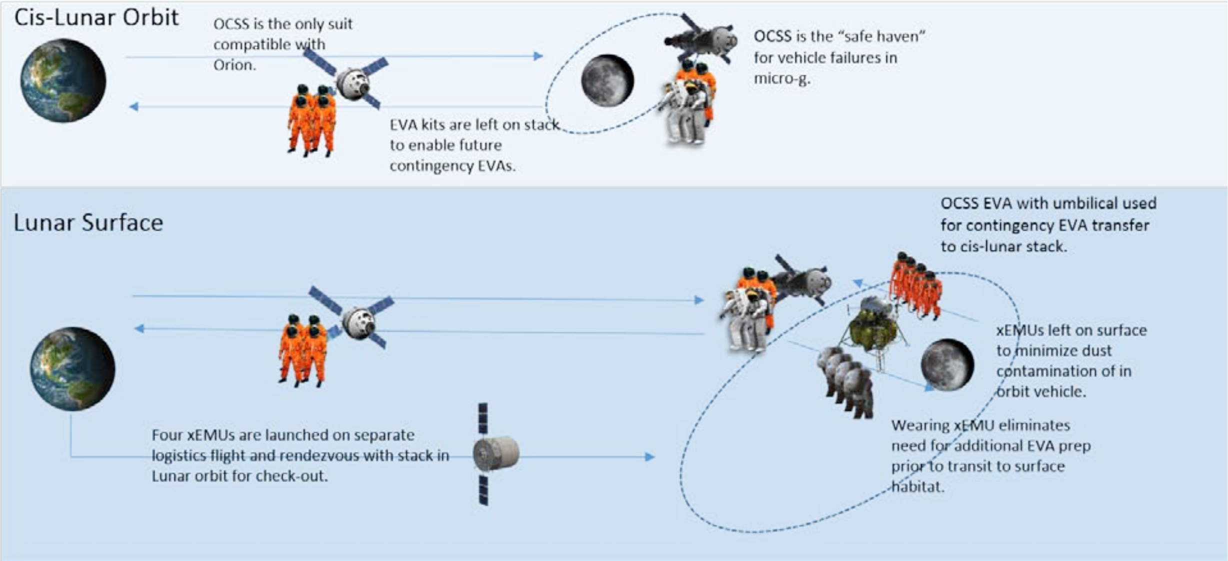


Figure VI-2 Exploration EVA System Ref. Architecture, HEO-001 Phase 1 and Phase 2 cis-lunar objectives

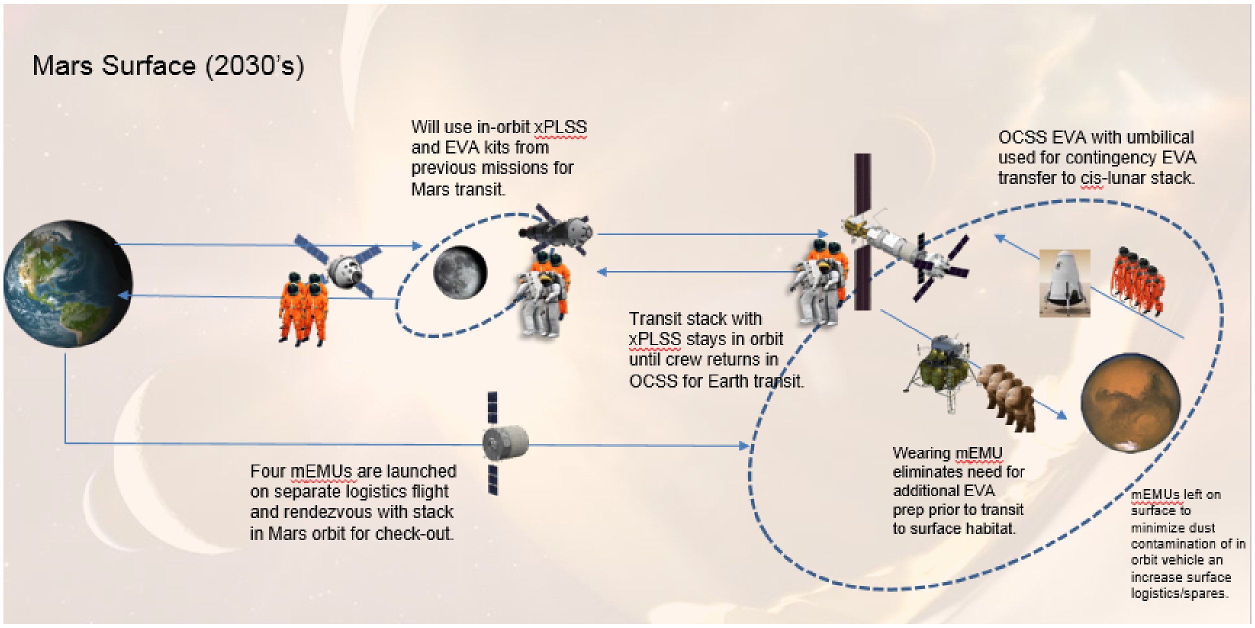


Figure VI-3 Notional Mars Mission Exploration EVA System

Note that cis-lunar space capabilities and deeps space EVA demonstration are depicted in Figure VI-2 while a notional Mars Mission Exploration EVA System is depicted in Figure VI-3. Phase 0 Demonstrations on ISS are not included in these graphics. As shown, the exploration system uses the xPLSS to enable limited EVA capability for missions in Cis-Lunar space. This may be necessary when constraints such as launch mass and distance from host spacecraft preclude use of umbilical with the LEA garment. As appropriate, the LEA system may be used with an umbilical for "Hatch-to-Hatch" transfers in fail-to-dock/fail-to-hardseal style contingencies. In later phases, the LEA garment becomes critical for ascent from partial gravity surfaces to minimize ascent mass while providing a pressure garment for such contingencies and controlling backwards contamination from suits used on the natural surface.

The combination of the xPLSS with the xPGS creates the xEMU which addresses all currently understood EVA needs for HEO-001's Phase 1 and Phase 2 Objectives. For HEO-001 Phase 0 demonstrations on ISS, the primary EVA objective would be to gain confidence in xPLSS performance. Focusing on the xPLSS during ISS Demonstrations could be enabled by reuse of contemporary ISS EMU Softgoods. Such an incremental step would defer the development of the complete xPGS, among other features. This configuration and approach is called “xEMU Lite”

It should be noted that the xPLSS and xPGS as envisioned are not “Suitport Compatible”.[9] Though they do not preclude the future development of the Suitport concept per se, the NASA Reference Design of the xPLSS and xEMU assume EVA access is achieved through a more conventional airlock volume for Phase 0, Phase 1 and Phase 2. Evolutions to Suitport compatibility later in Phase 2 (perhaps to support future objectives authored for preparation of Phase 3) are conceptually possible.

With some clarity on the system concept and how it supports the HEOMD-001 Phases and Objectives, the next step is the supporting documentation. The upper section of the Figure VI-4 below depticts the current reference requirements space for advanced EVA development. The upper section details the current reference “Level 1/2” document tree. It is also conceptually possible to utilize NASA’s Technology Development SE&I products as a pseudo-“Contractor Documentation” reference kit. This is depicted in the lower section of the same figure (Figure VI-4). The thought leading to this is that, though NASA’s Technology Development project is *not the only way* to meet the Agency’s top level programmatic SE&I structure, it is “at least one way” and is thus a useful example of how one might decompose to the lower levels of the documentation tree. Additionally this effort enables NASA to put it own draft requirements through a rigourous vetting by attempting a clean composition down to the specification level.

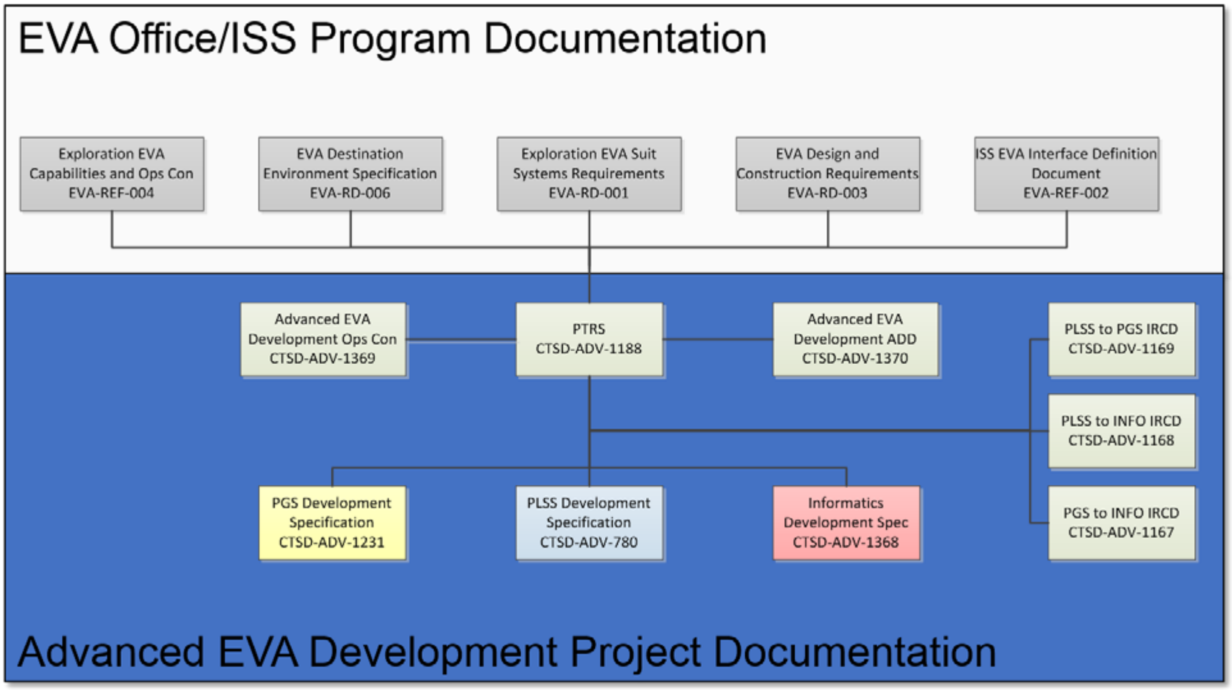
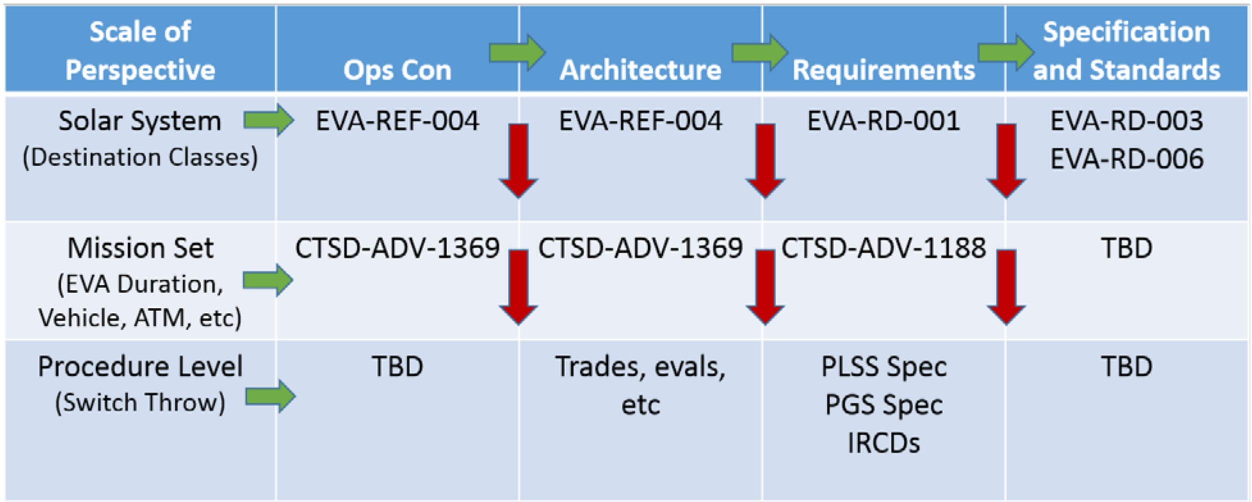


Figure VI-4 Advanced EVA Suit Reference Requirements Tree

Finally, a logical flow of “high to low, strategic to tactical” can be used to illustrate how these products trace to one another:



Scale of Perspective	Ops Con	Architecture	Requirements	Specification and Standards
Solar System (Destination Classes)	EVA-REF-004	EVA-REF-004	EVA-RD-001	EVA-RD-003 EVA-RD-006
Mission Set (EVA Duration, Vehicle, ATM, etc)	CTSD-ADV-1369	CTSD-ADV-1369	CTSD-ADV-1188	TBD
Procedure Level (Switch Throw)	TBD	Trades, evals, etc	PLSS Spec PGS Spec IRCDs	TBD

Figure VI-5 Notional Relationship and Flow of NASA Reference Documentation

The SE&I products described thus far have been coupled with inputs from across the NASA EVA Community to continually revise the EVA SMT Gap List and prioritize tasks for investment. FY17 efforts will continue to address and reduce cost, technical and schedule risk associated with future implementation phases of flight development. Independent of specific procurement strategies, the Agency must perform the tasks outlined in this plan to meet the objectives of maturing a reference suit system architecture and the broader EVA System. Therefore, this plan considers a wide portfolio of technology development and knowledge capture tasks that best support EVA's needs beyond Low Earth Orbit, reducing the gaps and risks identified in the EVA SMT Gap List and the HRP EVA Physiology Risk List[10]. It is the intent of the EVA office to maintain reference set of this documentation in a public space (https://www.nasa.gov/suitup/reference/). This should enable industry, academia, and international partners to stay abreast of the EVA community's current and best attempts to coalesce the gaps,objectives, architectures into a set of reference requirements and specifications for an initial advanced suit and other EVA systems. With more availability to reference document, the external community should be able to have improved and more specific communication with NASA.

Advanced EVA Development Project FY17 Tactical Plan

The Advanced EVA Development project is managed within the Space Suit and Crew Survival Systems Branch (JSC-EC5) of the Johnson Space Center's Engineering Directorate (JSC-EA) with project team members drawn from across the Center. The major hardware elements of the FY17 project are the xPLSS and the xPGS. The xPLSS development goals for FY17 include:

- Procurement of specific components to support component level technology maturation and eventual buildup of a high fidelity PLSS in the xPLSS -302 in FY18/19)
- Testing and performance evaluation of latest prototype components
- Initiation of System Analysis (e.g. Structural and stress) and model development
- Requirements / Specification development at the Subsystem and component level for the engineering reference design

The xPGS development goals for FY17 include:

- Testing of Z2 in the NBL with the primary goal of :
    - Validating Z-2 w/ PLSS package (moldline) volume for use on ISS Evaluating performance of the Z2 with EMU LTA, including use of EMU tools with Z2 upper torso architecture and suit usability with subjects across size range
- Testing of Z2 in the NBL with the secondary goal of :
    - Evaluate added performance from a highly mobile (planetary) LTA

- Evaluate capability of the Z2 8.0 psi operation

Supporting HRP bench mark testing, including testing of planetary prototypes in the ARGOS facility.

Exploration EVA Tools Technology Development Project FY17 Tactical Plan

The goal in EVA Tools over the next year is to improve the definition of geological science sample containment tool system architectures with specific input from the JSC science community. The current sample collection system revolves around a Sample Briefcase and two different driver methods, one manual and one powered. The prototypes and requirements for the two drivers are well understood, however the Sample Briefcase itself needs more development. The EVA Tools Team goals include:

- Iterating on the Sample Briefcase design with input from the JSC science community, focusing on areas such as materials of construction, types of sealing, levels of containment, witness plates, sample ports, and required cleanliness levels. Prototype assembly and testing not currently funded.
- Supporting ROM development and refinement for unique EVA tools
- Supporting the Z2 team with ISS EVA Tools for 1g fit checks.
- Supporting HRP benchmark testing with task board development and refinement.

VII. EVA Strategic Plan

Beyond the FY17 plans, what is the ultimate goal for EVA development? The answer: to develop and fly advanced EVA systems that will enable humans to explore beyond LEO and enhance our current capabilities in LEO. A primary objective towards meeting that goal is the development of an advanced flight EVA suit and close as many technology and knowledge gaps as possible. With several outcomes possible and uncertainty about the needs of human spaceflight exploration, no approved strategic plan beyond FY18 exists. The next flight development could serve one of the following purposes:

- EVA Flight Demonstrator on ISS
- Operational suit for the current ISS EMU
- Cis-Lunar EVA Microgravity EVA suit
- Lunar Surface EVA suit

Funding Constraints: NASA cannot afford to develop multiple suits so an obvious answer would be a single development that could accomplish all the above. However that too has many imbedded issues. For example, development of an EMU replacement could compromise the design of a Cis-Lunar EVA suit if not done in a modular approach. A “divide and conquer” approach whereby NASA partners with commercial industry or the international partners to create several versions of EVA suits is theoretically possible given the amount of technology development work pursued, however the commercial and international partner base in EVA flight development is relatively small. In any case, based on lessons learned, it should be a given that any suit intended to be used beyond LEO will be tested on ISS or another LEO based asset. Given that a suitable airlock on ISS exists that could accommodate a vast majority of the servicing of an advance suit, ISS is the perfect test bed for advanced EVA.

Schedule: The EVA community sees a few schedule “anchor” points in the near future. First, ISS is facing a baseline retirement date of 2024. Although this date has a good chance to be extended, it would be prudent to fly any new major system to ISS prior to this date. Additionally current architecture studies suggest the ability to have an EVA airlock capability on a Cis-Lunar vehicle stack as early as 2026. Assuming these dates held there is only 6 years (FY18 through FY23) to develop and launch a new system to ISS. This then would afford NASA approximately one year to evaluate and produce units for launch an use in Cis-lunar space (FY24 to FY25) Typical acquisitions of this size and scope would easily require 1-2 years to award. This arithmetic leaves approximately 4-5 years for flight development that supports both ISS and Cis-Lunar operation with an advanced EVA capability.

Acquisition: NASA has a myriad of approaches for acquiring new capabilities. This includes in-house development, typical competitive scenarios, as well as commercial approaches. No one acquisition model has been decided upon.

In summary, NASA has a queue of major decisions to make regarding EVA strategic needs. Until a major decision is made the EVA community will continue to work to enable any direction chosen. This includes:

- Maintaining open communication within NASA, industry & academia partners, international partners and the public … enable a diversity of ideas, communicate risks/needs, and facilitate coordination
- Focus on closure of technology and knowledge gaps
- Mature and validate advanced EVA systems and technologies, with goal of performing flight demonstrations
- Improve system models and perform system trades aimed at accelerated mission formulation and concept development
- Maintain, validate, and improve our cadre of requirements, interface standards, and operational concepts

VIII. Conclusion

The Exploration EVA System Development Plan is structured to support the critical needs of the ISS Program and achieve near term progress that is relevant to NASA's long term Human Space Flight goals. This plan is intended to create a coherent reference package that supports the development of the future Exploration EVA System with thorough and clear communication of all details available from the government. As such, it draws upon the needs highlighted in the ISS Risk Database through ongoing EVA flight operations as well as NASA's Global Exploration Roadmap (GER), Deep Space Gateway / Deep Space Transport mission scenarios and studies[11] and other studies such as FCT, MSC and the System Maturation Teams. The plan is structured such that any content that cannot be immediately invested in is clearly identified as such and tracked for future opportunities such as SBIR/STTR calls. This mechanism can also be used to highlight such gaps as potential risks during adoption of the Reference Architecture by projects, programs or acquisitions, communicating "where the government left off".

Regardless of what style or mechanism might be used for future flight hardware procurements, or what exactly the details of the parallel flight and technology development efforts look like, it is fully anticipated that whatever "flies next" in EVA will not be "the last EVA Suit humans will ever need". For instance, the state-of-the-art in materials and design for Pressure Garments are expected to provide adequate performance in all environmental parameters relevant to EVA through cis-lunar space and all the way to Mars orbit (including the moons of Mars) but are not appropriate for operations on Mars surface proper. Alternatively, the current state of the art in CO2 removal methods will need augmentation to extend operation from a vacuum environment (which all destinations short of Mars surface present) to the very low pressure atmosphere of Mars surface. As a third example, efforts focusing on increasing EVA Autonomy (solutions that facilitate EVA operations at destinations with extended communication delays or increased amounts of EVA) clearly require investment to prepare for long term planetary surface operations.

Thus, the EVA Strategic Development Plan is built to account for the evolution of human spaceflight through the 2020's, 2030's, and 2040's and allows for continued technology development that augments the flight capability developed in the upcoming years by ISS. The path from where EVA and Human Spaceflight are today, as operating on ISS, to Mars surface and vicinity operations can be summarized as follows:

- Operation of the ISS EMU through the early 2020's with demonstration of Exploration EVA capability per HEO-001's Phase 0 objectives.
- HEO-001 Phase 1 and Phase 2 cis-lunar space demonstration and validation, utilizing the EVA technology and capability as demonstrated on ISS in HEO-001's Phase 0.
- Planetary Surface EVA Tech Dev efforts increase as cis-lunar space flight operations mature through Phase 2 and parallel Technology Development efforts for partial gravity (such as Mars Surface) increase TRL.
- Deep space transit capability supported by EVA for Phase 3 operations "Beyond Earth-Moon System".
- Extended operations in Phase 3 including the Mars operations with on-ramping of technology development products into Mars Surface Suit in 2030's.

By providing a Reference Architecture that is modular in nature and supports an incremental development approach, the roadmap above allows for incorporation of disruptive technologies that emerge over the course of the 2020's and 2030's while ensuring the minimum amount of steady progress is being made towards Mars surface operations. Thus, the content within the Integrated EVA Development plan for the near term (FY17) orients NASA and EVA towards the Martian surface such that each step along the journey simultaneously facilitates success of flight operations while reducing future risk and uncertainty, culminating in an EVA System that can successfully conduct EVA's across all destinations humans may spacewalk within the inner Solar System.

Appendix – List of Sources for EVA Lessons Learned

EMU Lessons Learned Papers
AIAA-2012-3411-926   AEMU to Shuttle EMU Comparison
ICES-2015-327 EMU FIAR History
2005-01-3013 Lessons Learned Operating and Maintaining the EMU

EMU shoulder injury tiger team report NASA Technical Report TM-2003–212058
Williams DR, Johnson BJ (2003) NASA Johnson Space Center, Houston, TX

Extravehicular mobility unit training and astronaut injuries:
Strauss S, Krog RL, Feiveson AH (2005). Aviation, Space, and Environmental Medicine 76(5):469-74

Musculoskeletal injuries and minor trauma in space: incidence and injury mechanisms in U.S. astronauts.
Scheuring RA, Mathers CH, Jones JA, Wear ML (2009) Aviation, Space, and Environmental Medicine 80(2):117-24

EVA Knowledge Capture
US Spacesuit Knowledge Capture Series (http://nescacademy.nasa.gov/category/5/sub/27)

Mishap Reports
EVA-23 Water Intrusion Mishap Investigation Board Report
IRIS Case Number: S-2013-199-00005 (publicly available redacted version)

EVA Reference Documentation
EMU Mini Databook (EAR Export Classification: ECCN [9E515.a])
EMU Requirements Evolution (Rev. B 2005 - EAR Export Classification: ECCN [9E515.a])

EVA Operations Lessons Learned
Flight and Increment Lessons Center
EVA CCB lessons learned, Crew Consensus Reports, EMU Failure Tracking
https://nasa-ice.nasa.gov/portal/web/eva/flight-lessons-center (behind NASA firewall)

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[1] https://www.nasa.gov/sites/default/files/files/Olson_NACCapabilityDrivenRoadmap030612_508.pdf

[2] https://www.nasa.gov/content/nasas-journey-to-mars

[3] https://www.nasa.gov/sites/default/files/atoms/files/heomd_001_-_exploration_objectives_baseline_release_090716.pdf

[4] https://www.nasa.gov/suitup/reference

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[5] *“The NASA Presidential Transition Binder”*, https://www.hq.nasa.gov/office/pao/FOIA/Transition_Binder.pdf, *pg 315*.

[6] Campbell, C., “Advanced EMU Portable Life Support System (PLSS) and Shuttle/ISS EMU Schematics, a Comparison,” AIAA-2012-3411, *42nd International Conference on Environmental Systems*, AIAA, July 2012.

[7] https://www.nasa.gov/suitup/reference

[8] http://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_0_introduction_crosscutting_index_final_0.pdf

[9] Boyle, R., Mitchell, K., Allton, C., Ju, H., “Suitport Feasibility – Development and Test of a Suitport and Space Suit for Human Pressurized Space Suit Donning Tests,” AIAA 2012-3631, 2012, doi: 10.2514/6.2012-3631.

[10] https://humanresearchroadmap.nasa.gov/risks/risk.aspx?i=84

[11] https://www.nasa.gov/sites/default/files/atoms/files/march_2017_nac_charts_architecturejmf_rev_3.pdf