

Compatibility between Exploration EVA System and Exploration Spacecrafts

Christine N. Kovich¹

The Aerospace Corporation, at NASA Johnson Space Center, Houston, TX, 77058, USA

Caitlin E. Meyer²

NASA Johnson Space Center, Houston, TX, 77058, USA

Over the life of the Extravehicular Mobility Unit (EMU), numerous products detailing “how to build Extravehicular Activity (EVA) System hardware”, “how to interface with EVA System hardware” and “how to design hardware EVA will access and utilize” were generated to provide interoperability between a suited crewmember and the specified vehicle’s EVA task. Since the inception of these products, some have continued to receive updates due to the necessity of an on-going program while others remained unchanged for years and have led to discrepancies between the current accepted values and those considered outdated. For EVA-suited crewmember tasks beyond Low Earth Orbit (LEO), new vehicles need a single consolidated location for the best practices and lessons learned from the EVA Community. This paper outlines what common EVA compatibility design requirements are expected of an Exploration spacecraft that has interactions between the vehicle and an EVA suited crewmember for and an approach for standardizing EVA compatibility across various vehicles at various destinations. The approach of standardization allows for flexibility by tailoring the applicability to meet the EVA tasks required for that vehicle’s operation beyond Low Earth Orbit. This paper will also describe the broad difference between microgravity and partial gravity EVA compatibility and how those requirements were identified and will be informed.

Nomenclature

<i>APFR</i>	=	Articulating Portable Foot Restraint
<i>ARCM</i>	=	Asteroid Redirect Crewed Mission
<i>ARRM</i>	=	Asteroid Redirect Robotic Mission
<i>BAA</i>	=	Broad Agency Announcement
<i>BRT</i>	=	Body Restraint Tether
<i>CR</i>	=	Change Request
<i>CxP</i>	=	Constellation Program
<i>DOORS</i>	=	Dynamic Object Oriented Requirements System
<i>EHP</i>	=	Extravehicular Activity and Human Surface Mobility Program
<i>EMU</i>	=	Extravehicular Mobility Unit
<i>ESP</i>	=	External Stowage Platform
<i>EVA</i>	=	Extravehicular Activity
<i>FOD</i>	=	Flight Operations Directorate
<i>GP</i>	=	Gateway Program
<i>HLS</i>	=	Human Landing System
<i>HSM</i>	=	Human Surface Mobility
<i>ICD</i>	=	Interface Control Document
<i>ID</i>	=	Identification

¹ Requirements, Interface, & Verification System Engineer, EVA and Human Surface Mobility Program, NASA JSC, DI

² Requirements, Interface, & Verification Lead, EVA and Human Surface Mobility Program, NASA JSC, DI.

<i>IRD</i>	=	Interface Requirements Document
<i>IVA</i>	=	Intravehicular Activity
<i>JSC</i>	=	Johnson Space Center
<i>LEO</i>	=	Low Earth Orbit
<i>LTV</i>	=	Lunar Terrain Vehicle
<i>MBSE</i>	=	Model-Based Systems Engineering
<i>NASA</i>	=	National Aeronautics and Space Administration
<i>NG</i>	=	Next Generation
<i>ORU</i>	=	Orbital Replaceable Unit
<i>PDGF</i>	=	Power and Data Grapple Fixture
<i>PR</i>	=	Pressurized Rover
<i>RIV</i>	=	Requirement, Interface, and Verification
<i>SE&I</i>	=	Systems Engineering & Integration
<i>SME</i>	=	Subject Matter Expert
<i>SSP</i>	=	Space Station Program
<i>SSRMS</i>	=	Space Station Remote Manipulator System
<i>STS</i>	=	Shuttle Transportation System
<i>US</i>	=	United States
<i>WIF</i>	=	Worksite Interface
<i>xEMU</i>	=	Exploration Extravehicular Mobility Unit
<i>xEVA</i>	=	Exploration EVA Suit

I. Introduction

Back in 2012, the EVA Office was asked to develop relevant EVA requirements necessary for providing to future Exploration spacecraft that would need to be compatible with a new Exploration EVA (xEVA) Suit. This effort began with a review of the EVA Office-owned JSC 28918, EVA Design Requirements and Considerations¹ document to produce a set of design standards that would apply to future Exploration spacecraft or any other equipment that would interface with the EVA crewmember. The intent of this document was to capture the lessons learned by EVAs performed on the International Space Station (ISS). It helped to derive the EVA capability required for the proposed Asteroid Redirect Crewed Mission (ARCM) in 2016.

National and Aeronautics Space Administration's (NASA's) focus shifted in 2017 with the goal of returning to the lunar surface, so the EVA Office began working on assessing the use of the government Exploration Extravehicular Mobility Unit (xEMU) reference design as the base architecture for a suit that could be utilized in multiple destinations². This led to an extensive effort to review each of the EVA-related requirements and perform a comparison between ISS, Constellation Program (CxP), and various other Agency standards. This effort paved the way for a new document that would consolidate all of the EVA compatibility requirements into one document for missions beyond ISS.

II. Background

EVA Office historically utilized a *Generic EVA Compatibility* approach for ISS EVA requirements. Efforts extended from the late 1990s through early 2000s to provide a common source that included ISS lessons learned for all EVA requirements that could be used for all future Programs (e.g, creation of JSC 28918¹ in 2005). However, due to the lack of any new Programs on the horizon outside of ISS, and the ongoing churn of ISS to EVA documentation, resources were allocated mainly to sustaining the current active ISS Program documentation. JSC 28918¹ was never formally levied on the ISS Program due to it being interpreted as a "lessons learned" document. Consequently, JSC 28918¹ has never been updated. Instead a couple of key documents that provided the core set of requirements for development of EVA hardware and considerations for design of ISS vehicles and payloads that were generated in the late 1990s. The ISS Program started with these documents and the tailored implementation was through both SSP 30256, EVA Standard Interface Control Document (ICD)³ and SSP 57003, ISS External Payloads Interface Requirements Document (IRD)⁴.

The following subsections will provide a comprehensive overview for the process of developing a single source of documented EVA compatibility requirements and lessons learned that will be applied to future Exploration spacecraft hardware design.

A. Selection of Source Requirements Documents

The initial step involved reviewing JSC 28918¹ design considerations to determine the best approach for documenting a new philosophy going forward for EVA compatibility. JSC 28918¹ only encompassed some of the relevant design considerations needed to be compatible with the xEVA System. Therefore, additional source documents needed to be compiled that would provide the entire breadth of requirements to ensure that a future Exploration spacecraft would be compatible with the xEVA System.

This led to the construction of a single source of EVA compatibility requirements through assembling of all active EVA documents from the Space Shuttle Program (SSP), ISS Program, and CxP eras to assess those requirements that pertain to hardware compatibility with the xEVA System and operations. In addition, Agency standards were also reviewed to determine which were relevant to compatibility with the xEVA System. Around ten documents were selected that included requirements from hardware design documents^{5, 6}, JSC 28918¹, ISS EVA ICD³, ISS IRDs^{4, 7}, CxP Design and Construction Specification⁸, ISS Safety Requirements⁹, and Human Standards^{10, 11}.

B. Comparison Analysis of Source Requirements

The initial set of requirements utilized were those derived for JSC 66943, ARCM IRD Revision A back in 2016¹². Requirements were captured in a spreadsheet that allowed for traceability to the source parent. All of the source documents were reviewed, and a cross-comparison with relevant requirements was performed and recorded. This effort began in 2017 and included documentation of the following: whether the requirement was heritage Space Shuttle or ISS Program, source document and noted section, notes on requirement comparison analysis, observations, and recommendations for the EVA Compatibility requirement. The spreadsheet column for observations yielded many cases where there was overlap and redundancy of requirements found in multiple source parents. One key observation was that some of the source documents continued to receive updates due to the necessity for the ISS Program while others remained unchanged over the years. This led to discrepancies between the current accepted values in requirements versus those that were contained in outdated documents.

Compilation of this data was performed over the span of a couple of years. The longest portion of the process was the actual trace of a requirement to multiple source documents. Findings were documented in the requirement comparison column. Each proposed requirement was evaluated against the source document requirement and a recommendation was noted in the comment column.

III. Documenting Requirements and Best Practices/Lessons Learned

Once the comparison analysis had been performed, the next step was to determine the best way to document the EVA compatibility requirements. The EVA Office began the generation of a new single source document for EVA requirements in EVA-EXP-0035, Exploration EVA System Compatibility¹³ that was intended to be applied to future Exploration Programs and spacecraft.

The following subsections detail the implementation of EVA-EXP-0035¹³ document for compatibility with the xEVA System.

A. Defining EVA Compatibility versus EVA Interface Requirements

An important clarification involved defining what was considered to be an EVA compatibility requirement versus an interface requirement for the xEVA System to the Exploration spacecraft. The document did not include EVA interfaces that were considered to be internal to the vehicle such as spacesuit servicing, performance, and checkout equipment (e.g., items that directly interface with the suit such as fluid and electrical connectors) or non-mechanical Exploration Spacecraft to xEVA System (such as wireless communication, data, video, and audio). All of these items would be defined in the specific Program/Spacecraft IRD. In other words, the EVA Compatibility document defined what the requirements were for the pressurized suited crewmember interaction with the Exploration spacecraft, Orbital Replacement Units (ORUs), payloads, etc.

In addition, requirements that described the human-to-suit interfaces (like anthropometric requirements) or Intravehicular Activity (IVA) suit-to-vehicle interfaces were not included. Those standards and their requirement guidance would be included in the specific Exploration Program/Spacecraft implementation of NASA Human Standards¹¹.

B. Purpose and Scope

The EVA Compatibility document EVA-EXP-0035¹³ was ready for EVA community review by the spring of 2018. It contained the basic fundamental information required for building and verifying that hardware would be compatible with

pressurized EVA suited crewmembers to perform successful EVAs. It was to be used for the development of lower-level, program-specific requirements. The document was to act as a template for developing interface requirements between the xEVA System and an Exploration Program/Project/Spacecraft. Program/Projects/Spacecraft would not directly refer to requirements in this document nor directly verify to requirements, rather would tailor to that specific Program/Project/Spacecraft.

Values used for defining what compatibility with a pressurized space suit was based on the original EVA System from the Space Shuttle Program that was modified for ISS Utilization. Assumptions were that the new xEVA suit would either meet or exceed the capabilities of the original EVA System. As the new xEVA suit design matures, updates to the requirements would need to be made that reflect the improvement in capabilities being offered by the xEVA System.

C. Applicability

The requirements were applicable to the development of all Projects/Programs/Spacecraft that perform EVA operations or interact with the xEVA System. The document could be encountered by hardware providers as follows:

- 1) Exploration Spacecraft with EVA Capabilities Development – applicable to Exploration spacecraft that require EVA operations performing nominal and contingency: maintenance, repair, and replacement, payload, and science utilization.
- 2) xEVA Tools- applicable to all developed tools being utilized by the xEVA System.
- 3) xEVA suit - capabilities required of a vehicle or tool developer interfacing with a pressurized suited crewmember. xEVA suit developers will meet or exceed the current EMU design that drove the standards for compatibility between pressurized suited crewmembers, Exploration vehicles and xEVA tools. As the design matures, updates to the requirements would be made to reflect the improvement in capabilities being offered by the xEVA System.

All external hardware providers must make provisions to protect the EVA crewmember from anything that presents a danger or safety hazard.

D. Document Structure

Document revisions could cause cases where sections move; therefore, each requirement was uniquely numbered and identified by the presence of a tag. This requirements tag [EVA.SC.XXXX] provides a trace to historical information across multiple Program/Project/Spacecraft. In addition, the requirements tag was added as a column to the source document spreadsheet. It allowed for a trace mapping between the requirements that resided in the document and the source requirement from ISS historical documents.

The document was comprised of requirements that were categorized into the following EVA Compatibility topics:

- 1) Clearances (e.g., for translation path, pressurized glove, handrails/handhold, foot restraint)
- 2) Translation (e.g., translation path provision and diameter)
- 3) EVA Handling (e.g., for object mass, hatches, alignment features, pressurized gloved hand compatibility, labeling, hand tool operation, handrails, work envelope)
- 4) Worksite Outfitting (e.g., worksite mobility, field of view, dedicated worksites)
- 5) Loads (e.g., tether point, soft good tether point, microgravity induced-loads, EVA actuated loads, handrails, worksite interfaces)
- 6) Connectors (e.g., operation, accessibility, mating, coding, protective caps, alignment, design)
- 7) Fasteners (e.g., operation, compatibility with pressurized glove, hand and tool actuated, design)
- 8) Hardware Design (e.g., battery powered devices, common tools, cables, paint)
- 9) Safety (e.g., hazardous materials, shock hazards, touch temperatures, sharp edges, pinch points, burrs, emergency ingress, entrapment)
- 10) Environments (e.g., magnetic field, electromagnetic interference, voltage potential)

The requirements in the document provided a starting point for defining the minimum requirements and constraints that applied to performance, design, interoperability, maintainability, and safety applicable for performing successful EVAs. It was intended that the minimum set of requirements provided a form of interface control ensuring that all end items were compatible for interaction with the xEVA System during EVA operations.

The Baseline document contained a verification matrix that provided suggested verification methodology and was considered a starting place for verification development. Verification statements with success criteria would be included in a revision to the document. There were two Appendices included that captured lessons learned and Best Practices applied for performing successful EVAs. These Appendices provided context concerning the ISS EVA lessons learned that are worthy of consideration when designing Exploration hardware for EVA operations.

An additional Appendix provided a list of IVA/EVA tools and approved fastener drives in support of Exploration missions. This Appendix was invoked through a requirement as an attempt to reduce the number of tools and ensure utilizing only common tools and fasteners. The ISS Program currently has over 300 hand tools along with various maintenance kits, diagnostic tools, and parts kits. Due to mass constraints and volume limitations for Exploration destinations, providers of Exploration spacecraft/hardware, EVA tools, and xEVA suit would need to design their hardware to be maintained by a smaller set of common tools.

E. Common Requirements for EVA Compatibility

The most common group of requirements implemented in design of spacecraft with EVA capability are associated with EVA translation and worksite compatibility with the xEVA System. These types of requirements also take into consideration crewmember work volume, suited pressurized glove compatibility, structural loading, environments, and safety. EVA translation and worksite requirements have evolved over the course of the Space Shuttle and ISS Programs. The EVA translation path corridor defines the dimensions that provide clearance around the crewmember to perform the task. Any interferences into this path can provide potential hazards to the crewmember. An EVA worksite also requires specific clearance to translate to it, allow for crew stabilization, as well as clearance at the worksite to successfully perform the operations. A worksite can either free-float, dedicated, or robotic (in a foot restraint).

Figure 1 provides a view of the EVA crewmember egressing from the ISS Joint Airlock. A contiguous translation path usually begins with egress from the Airlock and continues to/from the dedicated worksite and concludes with ingress back into the Airlock. EVA translation paths are more than just the placement of handrails and tether point locations along a Spacecraft and requires analysis early in the design. This analysis provides the best locations for placing the path without restricting the vehicle operations as well as allows for safe and quick return to the Airlock in the case of an emergency. Translation paths must meet the EVA compatibility safety requirements. Design of EVA translation paths and worksites are critical for any Spacecraft or Integrated Stack (e.g., ISS) design so that is able to fully support EVA operations.

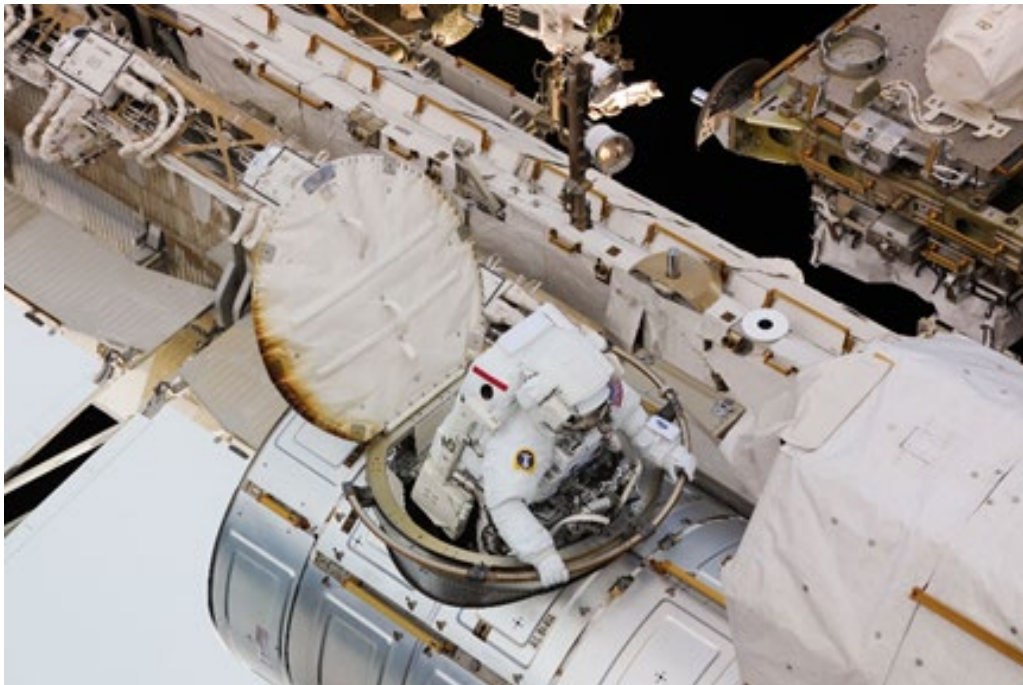


Figure 1. ISS Airlock Egress on US EVA 16 (iss024e16103).

Figure 2 illustrates the EVA translation path while an EVA crewmember is positioned at a dedicated worksite (in this case, ISS Node 1 Unity Module). Most translation paths along the ISS truss structures are not as encumbered as those that route through modules or interior to the truss structure. As noted in Figure 2, some of the translation paths can be quite constrained with other hardware or modules in the vicinity. Translation and worksite analysis provide

initial inputs into Spacecraft design to ensure that the EVA crewmember will be able to access all aspects of the EVA worksite. It is important to ensure that there is adequate corridor around the crewmember to allow for translation, taking into consideration the crewmember's work volume and potential for inadvertent contact with structure.



Figure 2. ISS EVA Translation on EVA3 Joint Expedition 28/STS-135 Joint Operations (iss028e005283).

Figure 3 demonstrates EVA translation along an ISS Spur. The ISS Spur provides a translation path from the Airlock to the truss structure (e.g., a handrail bridge between the ISS modules). Figure 4 is an example of translation along the US Laboratory Module. It also shows other module hardware, such as an umbilical and Power and Data Grapple Fixture (PDGF) which is located to the upper right of the crewmember. Figures 3 and 4 provide illustration of unencumbered EVA translation (e.g., does not include hardware that encroaches on the EVA crewmember work envelope). These figures represent what is anticipated on an Exploration Integrated Stack or Spacecraft.

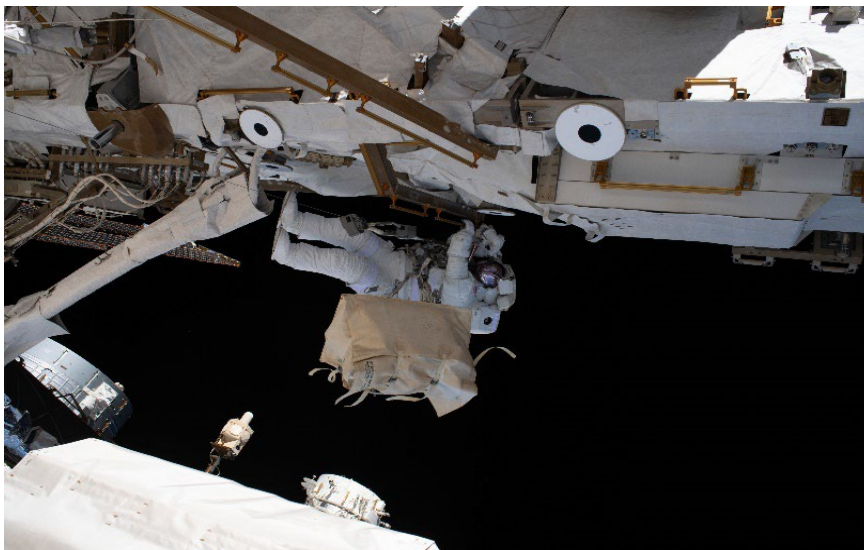


Figure 3. ISS EVA Translation (iss061e066433).

Mass handling of various size ORUs was common during assembly and maintenance of ISS. Figure 3 shows an EVA crewmember translating with the Large ISS ORU Transfer Bag on the Body Restraint Tether (BRT). The Large ORU Transfer Bag is an example of a smaller ORU that can be translated by an EVA crewmember and does not require the use of a foot restraint. Figure 5 is an example of an EVA crewmember ingressed in the Articulating Portable Foot Restraint (APFR) located on the end of the Space Station Remote

Manipulator System (SSRMS) while performing a mass handling task with an ORU (Nitrogen Tank). This type of

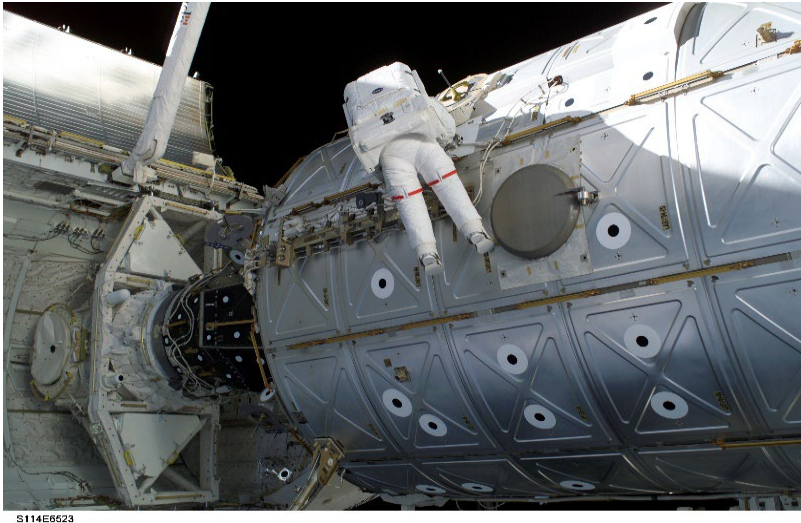


Figure 4. ISS EVA Translation on US Lab (s114e6523).

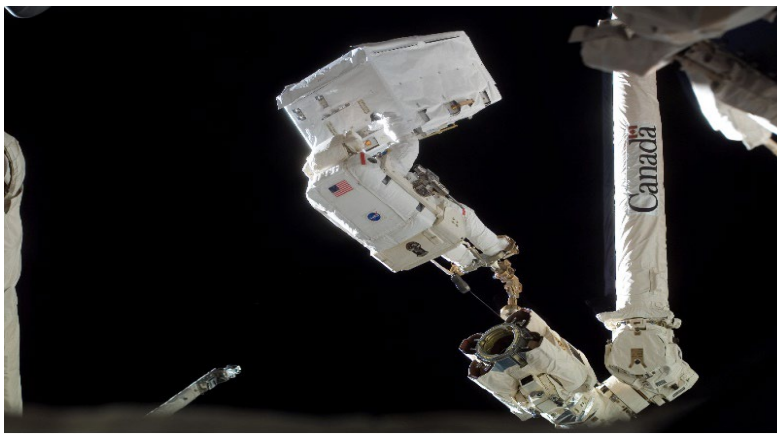


Figure 5. ISS SSRMS Mass Handling during STS-122 EVA 2 (s122e008149).



Figure 6. Worksite Operation during ISS EVA 50 (iss055e071264).

translation is associated with the relative mass, size, and shape the crewmember is to carry. Larger ORUs require that a crewmember is restrained on the robotic arm (e.g. SSRMS) to allow for two-handed manipulation.

The APFR shown in Figure 5 is also able to be installed on the ISS truss structure along with modules. In both cases, the APFR is installed in a Worksite Interface (WIF) socket that is structurally attached to the Spacecraft or Integrated Stack.

Crewmembers have a specific work volume for EVA translation and worksite operations. Figure 6 illustrates a crewmember operating a power tool at a dedicated worksite. The crewmember shown is installing a failed ORU onto the External Stowage Platform (ESP) 1 during ISS EVA operations. Crewmembers need to be restrained during power tool operations due to the high torque application. This worksite could have been accessed from an APFR from a WIF at the worksite, or by an APFR installed on the end of the SSRMS (e.g., robotic arm). Figure 6 is a good example showing the crewmember using a handling tool installed on the ORU as a handling aid versus the nominal ISS handrail or handhold.

Figures 1 through 6 are prime examples of EVA translation and worksite operations performed in the ISS microgravity environment. Translation paths and worksites are expected to be similar for Exploration Programs that have microgravity operations (e.g., Gateway). Partial gravity fields such as the Moon and

Mars are anticipated to be approached different.

IV. Benefits of EVA Compatibility Requirements Consolidation

An enlightening observation during the comparison analysis of the source documentation uncovered that there were discrepancies between the current accepted values in requirements versus those that were contained in outdated documents (reference Section IIB).

The following subsections provide context for the benefits of EVA compatibility requirements consolidation.

A. Single Source for EVA Compatibility Requirements

EVA-EXP-0035¹³ was considered the single source for EVA compatibility requirements and Baseline September 2018. Figure 7 shows the document flow based on the comparison analysis that was performed on all of the source documents. Figure 7 references the many source documents that were reviewed and illustrates how the content was consolidated into EVA-EXP-0035¹³. Sources included documents from Shuttle, ISS, and Exploration Programs. The continuation line for the documents in the ISS swim lane indicates those that are levied for EVA compatibility that fly to or on ISS.

B. Template for Exploration Program/Project/Spacecraft for Compatibility with the xEVA System

EVA-EXP-0035¹³ was considered to be a multi-purposed document. It was applicable to the xEVA System and invoked through SSP 51073, Exploration EVA Suit System Requirements Document as shown in Figure 7. An Appendix in SSP 51073¹⁴ delineates which requirements in EVA-EXP-0035¹³ were applicable to the xEVA suit. The Appendix also indicated those requirements that needed quantification for Spacecraft compatibility. As additional hardware elements (e.g., xEVA Tools) that comprise the xEVA System are defined, the Appendix would contain additional applicability matrices. EVA-EXP-0035¹³ was intended to act as a template for development of the interface

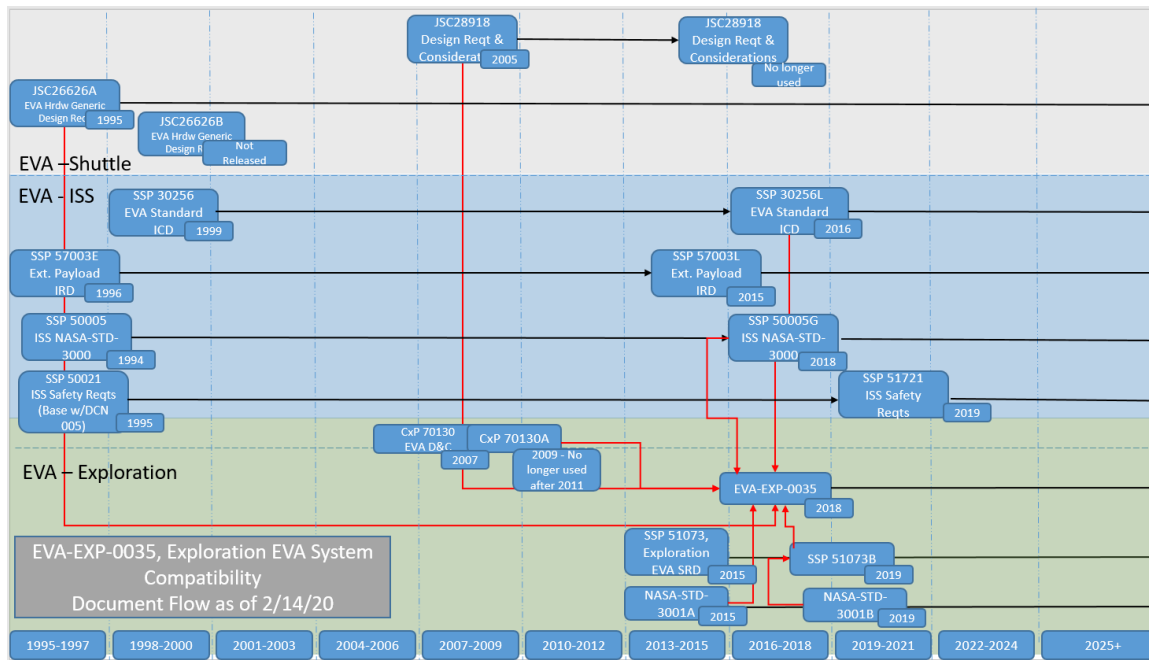


Figure 7. EVA-EXP-0035 Document Flow.

requirements on the Exploration Program/Project/Spacecraft to be compatible with the xEVA System. The Exploration Program/Project/Spacecraft would not reference EVA-EXP-0035¹³, rather would document the tailoring of requirements that are specific to their need in a separate Program-specific tailored version. The tailored version would align with the specific Program-specific concept of operations document.

C. Building document based on xEVA suit and levying on both xEVA System and Exploration Spacecraft/Payloads

EVA-EXP-0035¹³ allowed for taking a risk-reducing approach for levying EVA compatibility requirements for Exploration missions. In light of incompatible schedules and potential for multiple vendors on both sides of the interface, the document provided the capability for “meeting in the middle” (i.e., each side of the interface meets the xEVA suit work envelope, then it will ensure that the envelope would work with the new suit).

V. Tailoring for Multiple Program Use

The intent of EVA-EXP-0035¹³ document was to serve as the boilerplate template for tailoring to the needs of multiple Programs that will perform EVA operations. It was utilized to create tailored versions that served both Gateway Program¹⁵ and the Human Landing System (HLS)¹⁶ Program. Figure 8 provides the document tree flow for the EVA Compatibility documents through 2020.

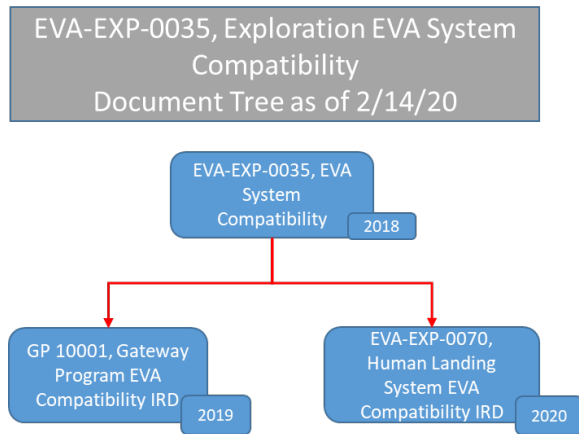


Figure 8. EVA Compatibility Requirements Document Tree.

The following subsections detail the process for establishing a set of EVA compatibility design requirements to ensure that both Gateway and HLS Programs will be compatible for contact/interaction with the pressurized suited crewmember.

A. Program Tailored Version Process

The first step was to utilize the Baseline EVA-EXP-0035¹³ as the initial document outline. An assessment of the Program concept of operations was performed and applied to the document through updates to the Introduction, Purpose and Scope Sections. In addition, a review of each requirement and subsequent rationale was conducted to determine if any of the requirement’s language needed to be modified to accommodate the Program proposed EVA operations. The Gateway Program was the

first to have a tailored version of EVA compatibility requirements in GP 10001, Gateway Program EVA Compatibility IRD¹⁵. The document went through a series of formal reviews by the Gateway Program organizations and International Partners including the EVA community prior to being Baseline in late August 2019.

Following the Baseline of the Gateway document¹⁵, a request was received to produce another tailored version for the HLS Program. A draft of EVA-EXP-0070, Human Landing System EVA Compatibility IRD¹⁶ was included on the HLS Broad Agency Announcement (BAA) Appendix H that was released in late September 2019. This document went through a formal review by the HLS and Gateway organizations and included the EVA community. It was approved for Baseline in February of 2020.

B. Applicability Matrix

The most important portion of the tailoring process included documenting the applicability of the EVA compatibility requirements to the various Exploration Elements/Modules/Spacecraft. An Appendix was added to capture the Spacecraft Applicability through the form of an applicability matrix. Assumptions for applicability assessment were outlined and a single requirements applicability matrix was generated. Each requirement was listed with the appropriate document section and requirement tag. This was especially important for Gateway Program as there it consists of multiple modules, robotic arm, and external payloads.

Examples of questions to consider when ascertaining the applicability of a given EVA compatibility requirement to a Spacecraft were as follows:

1. A Spacecraft that is considered to be a visiting vehicle that could protrude into an existing Integrated Stack EVA translation path or a worksite that may contain a minimal subset of EVA compatibility requirements applied through a Visiting Vehicle IRD:

- a. Assumes that the visiting vehicle requires no planned or contingency EVA. Visiting vehicle hardware near the EVA translation paths and worksites will meet the EVA safety requirements to protect EVA crewmembers as well as the visiting vehicle hardware.
 - b. If determined that the visiting vehicle will have planned or contingency EVAs, then the vehicle must meet the entire set of EVA compatibility requirements based on the applicability matrix in the Appendix (e.g. for Gateway visiting vehicles this is GP 10001¹⁵).
2. Decide if EVA capability will be needed:
 - a. If applicable, add translation associated requirements such as pressurized glove compatibility, handrail requirements (including structural/crew-induced loading and incidental contact), EVA thermal/safety requirements (sharp edges, pinch points, touch temperature, etc.), labeling, field of view, mobility, visual contrast, environmental.
3. Will there be dedicated EVA worksites:
 - a. If applicable, add all of the requirements outlined in EVA capability (see #1).
 - b. In addition, worksite requirements (including structural/crew-induced loading and incidental contact), work envelope, worksite restraints, ingress/egress aids.
4. Will there be ORUs or critical payloads (aids in determining applicability of EVA fasteners and connectors):
 - a. If applicable, add all of the requirements outlined in EVA capability (see #1) and dedicated EVA worksites (see #2).
 - b. In addition add EVA fasteners and connectors.

C. Additional Revisions of Program Tailored Versions

Gateway Program requested a new revision for GP 10001¹⁵ to close open issues and add verification statements. GP 10001 Revision A¹⁸ was a quick turnaround change that received formal approval and released in late April 2021.

Over the next couple of years, HLS Program matured and established its first contract for the Artemis III initial mission to the lunar surface. By 2021 a new revision to EVA-EXP-0070¹⁶ was needed to support HLS Partner (vendor). EVA-EXP-0070 Revision A + HLS-MD-0001¹⁹ went through review by both HLS Program and the EVA Office and was formally released in October 2021.

HLS Program expanded scope to include lunar surface missions beyond Artemis III and required an additional revision. The next revision was broken into two, an initial EVA-EXP-0070 Revision B²⁰ released in January 2022 followed closely by a management directive to provide requirement clarifications that resulted in EVA-EXP-0070 Revision B + HLS-MD-0010²¹ released in April 2022.

D. Transition from EVA Office to EVA and Human Surface Mobility (HSM) Program (EHP)

NASA announced formulation of a new Program in early 2022 that would encompass the work performed in the EVA Office along with needs for Human Surface Mobility Assets, such as rovers on the lunar surface. EHP was kicked off and spent the next several months constructing the Program structure. EHP includes three Projects: EVA Development (who will manage the new xEVA suit and tools through a service contract), Lunar Terrain Vehicle (LTV) and Pressurized Rover (PR).

EHP worked closely with Gateway and HLS Programs to provide the necessary revisions to the tailored Program EVA Compatibility documents. HLS Program received comments from sustained lunar industry on EVA-EXP-0070 Revision B + HLS-MD-0010²¹ that required an additional revision. A quick turnaround Change Request (CR) was processed with formal approval to release EVA-EXP-0070 Revision C²² by the end of June 2022. After several revisions to the HLS tailored version, a revision to GP 10001¹⁸ was needed to ensure consistency between the Programs, mainly with regards to requirements applicable in the microgravity environment. A change was implemented to align microgravity requirements and close open work. GP 10001 Revision B²³ was formally approved and released in August 2022.

Over the first year of EHP, it became evident that trying to manage three different versions of EVA Compatibility documents was becoming a challenge. The initial approach involved working with HLS Program to hand over configuration management of EVA-EXP-0070²² from HLS to EHP. The document would be processed on an EHP CR with Joint Program Boards required for approval.

E. Partial Gravity Requirement Gap Assessment Process

In the summer of 2022, the EHP Systems Engineering & Integration (SE&I) Requirements, Interfaces and Verification (RIV

Team) began preparing a draft Revision A for EVA-EXP-0035¹³. Intent was to incorporate updated requirements in both GP 10001²³ and EVA-EXP-0070²² to support the LTV draft Request for Proposal (dRFP) at the end of September 2022. While working on this draft document, the EHP RIV team continued to assess the open work to the documents and potential updates for the partial gravity environment. The draft EVA-EXP-0035 Revision A²⁴ LTV dRFP version was never baselined but was provided as draft document at the end of September 2022.

In September 2022, the RIV team convened several Subject Matter Experts (SMEs) to evaluate the existing EVA compatibility requirements. For each requirement, the team asked the following questions:

1. What is the intent of the requirement?
2. Is the intent applicable to partial gravity environment?
3. If yes to #2, can the existing requirement or rationale be modified to include partial gravity intent?
4. If no to #3, is the requirement needed?

The initial assessment resulted in the following summary:

- RIV Team identified that 122/138 requirements **WERE** applicable to partial gravity environment.
- Handrails and tethers: RIV team met with Flight Operations Directorate (FOD) and Safety to confirm partial gravity applicability for handrails and tethers on the lunar surface.
- Missing requirements: RIV identified four new requirements for Partial Gravity.

The RIV Team was provided an opportunity in October 2022 to perform a quick turn-around CR on EVA-EXP-0070²². Intent of the CR was to impact HLS provider contracts in support of March 2023 milestone date. It included results from the partial gravity requirement assessment with an extensive review and coordination among EVA stakeholders to provide the best EVA compatibility requirement updates. EVA-EXP-0070 Revision D²⁵ was recently approved by Joint Program Boards in mid-February 2023 and formally released to meet HLS milestone deliverable.

F. EHP Re-evaluation of approach for EVA Compatibility documents

The RIV Team was given an action from EHP Program management to determine feasibility of combining EVA compatibility requirements with physical interface documents to minimize the number of documents that EHP manages and provides to the community. Currently the documents are split between “EVA Compatibility” and “Vehicle Interfaces” and tailored for the External Program partners. This structure is made complex with the potential of multiple suits, landers, and exploration destinations. In addition, it involves multiple revisions or potential for requirements being out of sync between the External Programs and EHP.

The RIV team provided recommended proposal to the EHP Control Boards to consolidate the three documents into one EVA compatibility document. EHP Control Board approved the recommendation in the beginning of March 2023. The new document (draft EHP-10028²⁶, Exploration EVA (xEVA) System Compatibility Standards)) will have an associated applicability matrix for EHP Projects as well as External Programs/spacecraft/payloads, etc. It also allows for decoupling EVA compatibility requirements from physical interface requirements. Further work is involved in obtaining both Gateway and HLS Program’s acceptance of EHP’s recommended approach and implementation.

G. Providing Traceability between Programs

Traceability is an important component in requirements development. According to the NASA Systems Engineering Handbook, “complete and thorough requirements traceability is a critical factor in successful validation of requirements.”¹⁷ As discussed in Section IIID, the requirements tag [EVA.SC.XXXX] provides the capability to trace through multiple Program/Project/Spacecraft utilization. This tag, or static Identification (ID) number, is what will be used for traceability within a Model-Based Systems Engineering (MBSE) platform. Currently the requirements for EVA-EXP-0035¹³ reside within the Cradle® requirements management tool, while the Gateway GP 10001¹⁵ and HLS EVA-EXP-0070¹⁶ reside within the Dynamic Object-Oriented Requirements System (DOORS) Next Generation (NG) requirements tool. Import/export between the two requirements database is a beneficial resource as it provides the flexibility to maintain traceability between the multiple Programs.

No further traceability within the requirements database has been pursued since the initial Baselining of the three versions of the EVA Compatibility documents. An assessment was performed by EHP to determine what requirements management tool would be utilized going forward. After initial discussions with Gateway and HLS Programs, it was determined that EHP would utilize DOORS NG to manage requirements documents owned and managed by EHP. There is future work to implement this with the EHP documentation, including the new draft EHP-10028²⁶.

VI. Conclusion

It is vital that we learn from past Program's accomplishments as well as those failures that have helped to shape the way we perform EVAs today on ISS. EHP-10028²⁶ will become the consolidation of all EVA compatibility versions into a single document providing guidance within EHP Projects and External Programs/payloads. It is expected that any new xEVA Suit will either meet or exceed the capabilities of the heritage EMU. As the xEVA Suit design matures and/or as other suppliers of xEVA System hardware are identified, updates to the EVA compatibility requirements will be proposed that reflect the improvement/changes in EVA capabilities.

EVA-EXP-0035¹³ was the genesis for providing initial Exploration Programs/Projects/Spacecrafts the ability to tailor and determine which requirements are applicable to their System. EHP approved consolidating the Program-tailored versions into EHP-10028²⁶ that allows for one document to provide the set of EVA compatibility requirements that will include applicability matrices for EHP Projects, External Programs (Gateway and HLS) and any future spacecraft/payloads or Projects. The capability to standardize the EVA requirements that enable Exploration Programs/Spacecraft compatibility with the pressurized suited crewmember is a crucial step forward in achieving successful EVA operations across any destination that NASA dreams to pursue.

Acknowledgments

We would like to acknowledge the work of the entire EVA community for the support and exhaustive requirements review performed during the process of developing a single source document for EVA Compatibility requirements in 2018. The EVA Office provided the help needed to develop, review, and implement these EVA Compatibility documents. Thanks to Jesse Buffington and John Swatkowski of the EVA Office for assisting in getting the initial Baseline of EVA-EXP-0035¹³ formally approved and released. I extend additional thanks to Natalie Mary, Brian Johnson, and Brian Alpert from the EVA Office, who provided help in the coordination efforts with Gateway and HLS Programs on the tailoring of EVA compatibility requirements for Baseline GP 10001¹⁵ and EVA-EXP-0070¹⁶. In addition, I would like to extend a special acknowledgement to Lori Crocker and Maria Tullar for the guidance and historical EVA requirements background that helped to shape the final products Baseline EVA Compatibility documents.

During the maturation of the EVA Compatibility requirements and various Program-tailored versions, we appreciated all of the assistance from the EVA community and Program SE&I counterparts. This was especially beneficial during the transition from the EVA Office to the new Program (EHP) in early 2022. Since formulation of EHP, I am thankful for the support from my co-author Caitlin Meyer and fellow RIV team members. This journey has truly been a team effort and am proud of the progress we have made in getting to where we are today.

References

- ¹Crocker, L., Stewart, C., Adams, R., Nickel, G., Tullar, M., "EVA Design Requirements and Considerations," JSC 28918 Baseline, February 2005.
- ²"Moon to Mars Enterprise (M2ME) Decision Memorandum Surface Suits", M2ME-DM-0001.
- ³Collins, D., "International Space Station Program Extravehicular Activity Standard Interface Control Document", SSP 30256 Revision J, October 2012
- ⁴Walls, B., "International Space Station Program External Payloads Interface Requirements Document", SSP 57003 Revision L, March 2016
- ⁵Adlis, D., "Extravehicular Activity (EVA) Generic Hardware Design Requirements", JSC 26626 Revision A, May 1995
- ⁶Crocker, L., "Extravehicular Activity (EVA) Generic Hardware Design Requirements", JSC 26626 Revision B DRAFT, June 2006, (unpublished Draft)
- ⁷Weirauch, A., "ISS Pressurized Volume Hardware Common Interface Requirements Document", SSP 50835 Revision D, April 2013
- ⁸No author listed, "Extravehicular Activity Design and Construction Specifications", CxP 70130 Revision A, November 2009
- ⁹No author listed, "ISS Safety Requirements Document", SSP 50021 Baseline Incorporates DCN-005, November 2013
- ¹⁰Collins, D., "ISS Flight Crew Integration Standard", SSP 50005 (NASA-STD-3000/T) Revision F, January 2015
- ¹¹Squires, A., "NASA Space Flight Human Standard Volume 2: Human Factors, Habitability, and Environmental Health, NASA-STD-3001 Volume 2" Revision A, February 2015
- ¹²Kovich, C, Morgan, B., "Asteroid Redirect Robotic Mission (ARRM)-Asteroid Redirect Crewed Mission (ARCM) Interface Requirements Document", JSC 66943 Revision A, February 2017
- ¹³Kovich, C., "Exploration EVA System Compatibility", EVA-EXP-0035 Baseline, September 2018
- ¹⁴Kovich, C., "Exploration EVA Suit System Requirements Document", SSP 51073 Revision B, December 2019

- ¹⁵Kovich, C., “Gateway Program EVA Compatibility Interface Requirements Document”, GP 10001 Baseline, August 2019
- ¹⁶Kovich, C., “Human Landing System EVA Compatibility Interface Requirements Document”, EVA-EXP-0070 Baseline, February 2020
- ¹⁷Hirshorn, S.R., Voss, L.D., Bromley, L.K..., “NASA Systems Engineering Handbook”, NASA SP-2016-6105 Rev 2/HQ-E-DAA-TN38707, February 17, 2017, URL: <https://ntrs.nasa.gov/search.jsp?R=20170001761> [acquired February 23, 2017]
- ¹⁸Kovich, C., “Gateway Program EVA Compatibility Interface Requirements Document”, GP 10001 Baseline, August 2019
- ¹⁹Kovich, C., “Human Landing System EVA Compatibility Interface Requirements Document”, EVA-EXP-0070 Revision A + HLS-MD-001, October 2021
- ²⁰Kovich, C., “Human Landing System EVA Compatibility Interface Requirements Document”, EVA-EXP-0070 Revision B, January 2022
- ²¹Kovich, C., “Human Landing System EVA Compatibility Interface Requirements Document”, EVA-EXP-0070 Revision B + HLS-MD-0010, April 2022
- ²²Kovich, C., “Human Landing System Program EVA Compatibility Interface Requirements Document”, EVA-EXP-0070 Revision C, June 2022
- ²³Kovich, C., “Gateway Program EVA Compatibility Interface Requirements Document”, GP 10001 Revision B, August 2022
- ²⁴Kovich, C., “Exploration EVA System Compatibility”, EVA-EXP-0035 Draft Revision A, September 2022 (unpublished Draft)
- ²⁵Kovich, C., “Human Landing System Program EVA Compatibility Interface Requirements Document”, EVA-EXP-0070 Revision D, February 2023
- ²⁶Kovich, C., “Exploration EVA (xEVA) System Compatibility Standards”, EHP-10028 DRAFT, May 2023 (unpublished Draft)