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EVA OFFICE
EXTRAVEHICULAR ACTIVITY (EVA) AIRLOCKS AND ALTERNATIVE INGRESS/EGRESS METHODS DOCUMENT

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Executive Summary

This document captures the currently perceived vehicle and EVA trades with high level definition of the capabilities and interfaces associated with performing an Extravehicular Activity (EVA) using an exploration EVA system and ingress/egress methods during future missions. Human spaceflight missions to Cislunar space, Mars transit, the moons of Mars (Phobos and Deimos), the Lunar surface, and the surface of Mars will include both microgravity and partial-gravity EVAs, and potential vehicles with which an exploration EVA system will need to interface. In order to build an airlock compatible with the EVA suit, the interfaces must be understood. This document captures the current EVA assumptions and the trades and details needed from the vehicle-side to provide further detail to these EVA interfaces and operational concepts.

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TABLE OF CONTENTS

SECTION **PAGE**

APPENDIX

TABLES

FIGURES

1.0 INTRODUCTION

National Aeronautics and Space Administration's (NASA's) EVA Office, EVA System Maturation Team (SMT), and the Human Exploration Office have identified exploration Extravehicular Activity (EVA) suits as a high priority requirement to support any of the Design Reference Missions (DRMs) currently under consideration. Many of these DRMs include alternative ingress/egress methods which aim to provide the capability for high frequency EVAs, or readily available EVA capability, with dust mitigation. While there is not an impending need for readily available EVAs with dust mitigation in near term DRMs, it could help buy down risk to test the end-to-end operations in advance to prove the technology as well as the long-term effects of alternative spacecraft atmospheres on the human prior to getting to Mars and using it for mission success. Figure 1-1 shows potential phases of exploration.

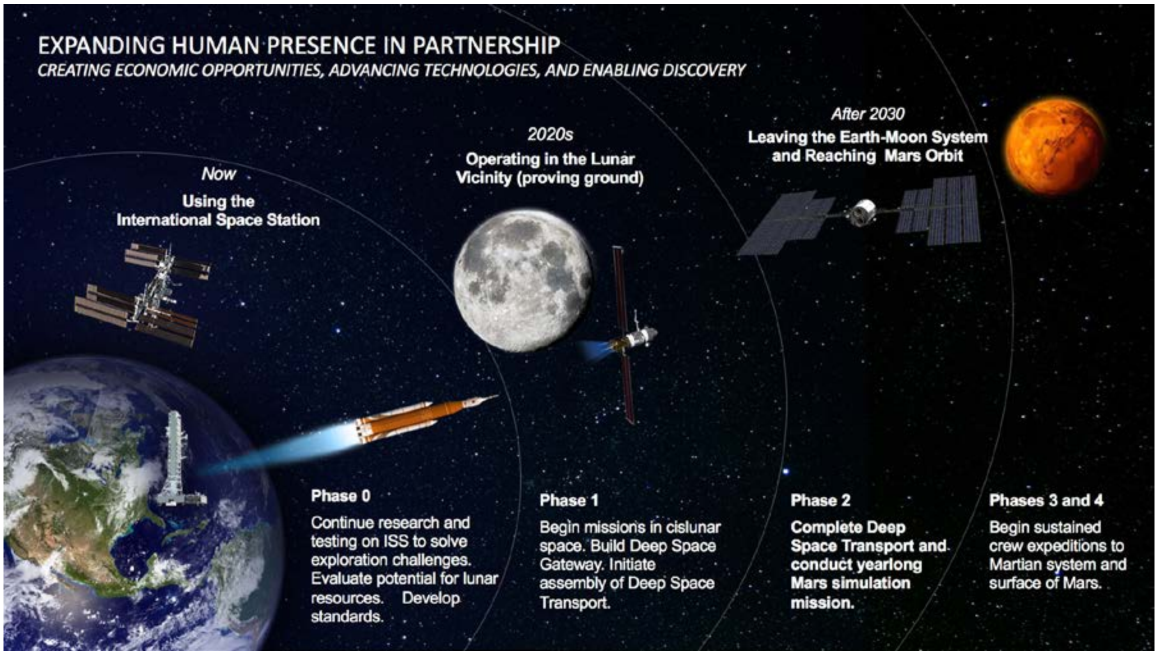


FIGURE 1-1 NASA'S EXPANDING HUMAN PRESENCE IN PARTNERSHIP, 2017

There are many variables to be balanced when evaluating the interfaces for alternative airlock concepts and exploration EVA suit compatibility. Ongoing technology development efforts are maturing new technologies for new exploration EVA suits and Portable Life Support Systems (PLSS) while reducing remaining operational risks for the suit. The same must be done for any new ingress/egress technology. This "stepping stone" approach parallels the current build, test, and learn methodology and allows time for agency maturation of flight/mission needs.

The EVA Office has assessed interfaces and impacts to the extent possible, though the extent of this is limited without a partner on the vehicle side. Currently, there are no funded projects/vehicles that are analyzing alternative airlock interfaces from a vehicle perspective. An ISS concern (#6458 in the ISS Program's Integrated Risk Management Application (IRMA)) describes the high level impacts to an exploration EVA suit compatible with current understandings of alternative ingress/egress methods, namely the suitport concept. These will be discussed in further detail in this document. To understand what can be done to reduce these impacts before building a suit compatible with suitport functionality or any other alternative airlock concept, a vehicle assessment is necessary. Other airlock concepts with less severe suit impact concerns are described in this document along with new functional needs for long duration missions in a partial gravity surface environment such as suit maintenance and dust mitigation.

In order to support EVA strategic planning for any future missions (with the ultimate goal of a Mars surface mission), it is valuable to understand the key Figures of Merit (FOM), such as mass, volume, consumables, etc. associated with ingress/egress methods from the vehicle perspective.

1.1 PURPOSE AND SCOPE

This document is intended to record and organize trades for future exploration EVA capability that addresses needs for ingress/egress methods and vehicle impacts. Once trades have been established/narrowed down, the structures and masses, volumes, and consumables can be understood from the vehicle perspective, possibly allowing future projects a path forward instead of immediately assuming state of the art equipment as appropriate for the future of human space flight. Sections 2-5 provide general background details of EVA, alternative airlock concepts and other methods of ingress/egress, as well as past trade studies which have been performed. These sections are intended to provide a consolidated review-form product which fulfills the role of a "primer" for ingress/egress methodologies across all of human spaceflight and thus can be used to form a basis of conversation for where the state of the art in both flight hardware and concept articulation currently is. Section 6 then addresses the current agreed upon EVA community assumptions given to each feasibility vehicle concept project that arises. Section 7 presents future trades to be considered when planning missions and vehicles capable of performing EVAs, with particular emphasis on documenting the various issues and FOMs that prove particularly difficult to resolve without a multi-party analysis that includes spacecraft/vehicle stakeholder participation. Section 8 provides a quick summary and Section 9 captures all the references that are cited throughout the document. This document does not reflect whether or not high frequency, readily available EVAs are a requirement in a particular DRM. That is a programmatic level trade and is specific to the destination, mission duration, and objectives of the mission.

1.2 CHANGE AUTHORITY/RESPONSIBILITY

Proposed changes to this document shall be submitted by an EVA Management Office Change Request (CR) to the EVA Configuration Control Board (EVA CCB) for consideration and disposition.

The appropriate NASA Office of Primary Responsibility (OPR) identified for this document is the EVA Office. As such, the EVA CCB manages this document on behalf of the International Space Station (ISS) Program as the delegated authority from the Space Station Program Control Board (SSPCB) per ISS MD 1049, Charter for the EVA CCB.

2.0 BACKGROUND

Missions to destinations beyond Low Earth Orbit (LEO) will affect all exploration EVA suit subsystems including the suit (or pressure garment), the PLSS, and the Informatics system (INFO). In addition, such missions will force the design of an exploration EVA suit to consider new challenges involving limited resources/consumables resupply, communication delays, harsher environments (e.g. thermal, prolonged radiation exposure, micrometeoroid impingement, increased thermal gradients and dust mitigation), and different gravity fields.

Necessary for ISS construction and maintenance, ISS EVAs were implemented with repurposed Shuttle EVA suits and a modified Shuttle airlock that includes additional volume using a shortened pressurized module as an equipment lock. As the Agency continues looking at missions in cislunar space, Mars surface, and Mars vicinity destinations, it is clear that an exploration EVA suit architecture must be more robust, more reliable, and operate more efficiently than the current ISS EVA Mobility Unit (EMU) fleet and ISS airlock. The architecture should also be extensible to Mars surface pioneering efforts and capable of supporting more frequent, readily available exploration EVAs (including surface and microgravity ops) while minimizing needed consumables, spares, crew time, and planetary protection impacts. Timely EVA is a key FOM in the efficacy of exploration and a primary product for exploration mission success.

These mission performance improvements are believed to drive a need for an ingress/egress method beyond conventional airlocks. For the purpose of this document, the various concepts that might meet this need will be collectively referred to as ingress/egress methods. Features and capabilities that have been widely discussed for an ingress/egress method include:

- A rear-entry suit donned/doffed through a vehicle bulkhead
- Short-duration EVAs which become feasible due to reduced EVA prep time
  - Alternative spacecraft atmospheres reduce amount of prebreathe time (Abercromby, et al., 2015)
- Multiple EVAs during the same day, multiple days per week
  - Reduced crew fatigue/injury
  - Increased crew autonomy
- Reduced consumables use such as cabin atmosphere (specifically for the suitport concept)
- Increased dust mitigation/planetary protection

Concepts including some or all of the features listed above include the suitport concept, the rear-entry airlock or suitlock, and a suitport-airlock combination. These will each be described in further detail in Section 4.

During the Constellation Program (CxP), risks were identified for an exploration EVA suit and PLSS compatibility with a suitport. Several trade studies were introduced to delve deeper into the operational concepts and mechanisms of different concepts. These trades are described in further detail in Section 5.
While these studies began to point the way to complete solutions, trades and implications associated with these concepts need to be further assessed. This document has been organized to guide the reader through the historical context as well as the trades and analyses that need to be performed in order to develop an ingress/egress method.

After Constellation, concentration began to focus more on near term deep space, mainly cislunar, with a future destination of Mars. Section 6 was introduced to be available to provide a consolidated list of EVA assumptions to feasibility study teams in order to guide them in conceptual airlocks and the interfaces needed by EVA.

3.0 STATE OF THE ART AND KNOWN CHALLENGES

Current State of the Art (SoA) technology is the ISS Quest Joint Airlock (reference Figure 3-1).

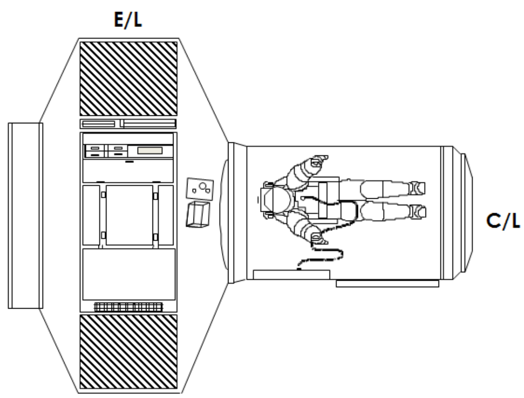


FIGURE 3-1 SOA ISS QUEST JOINT AIRLOCK

The ISS Quest Joint Airlock system includes:

- Two isolatable volumes independent of the ISS vehicle (Dual Chamber Airlock)
  - The total Joint Airlock pressurizable volume is 1108.25 ft^3 (31.4 m^3), the Crew Lock volume is 200.61 ft^3 (5.6 m^3), and the Equipment Lock volume is 907.64 ft^3 (25.7 m^3)
  - This volume is different from the functional working activity volume of the ISS crew lock, which is measured internally
  - Equipment lock CAD models and physical measurements of training unit show a 100" x 53", or a 137.82 ft^3 cylindrical functional working activity volume with hatch closed
- Dual suit capable (both EMU and Orlan (RS) suits – this has not been tested on-orbit as the RS airlock is closer to the RS segment worksites; however, it has been ground tested
  - There were unresolved questions about how to scrub the water loops post RS/Orlan use in order to not contaminate the EMU water loop systems (Orlan used silver nitrate, EMU used iodine. Silver nitrate is not compatible with EMU water systems)
  - The risk to EMU capability was determined too great, and the ISS 3 Increment Manager directed a stand down from demonstrating the Orlans in the US airlock

The crew lock external volume is shown below (drawing ref. 683-51960):

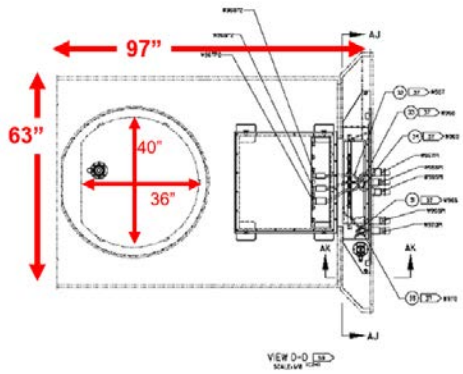


FIGURE 3-2 CREW LOCK

- 4.25 m^3 or 150 ft^3 habitable crew lock volume which accommodates two suited pressurized crewmembers; however, the shortest distance between the top of the UIA to the EVA handrail opposite of it drops the internal habitable volume closer to 137.82 ft^3 based on measurements and CAD (~5.5 m^3 or 194.23 ft^3 internal pressurized volume, CX reports as 200.2 ft^3)
  - Majority of atmosphere consumables reclaimed into vehicle stack during depressurization prior to opening the hatch with a 1.5 kW depress pump (two 30 minute cycles during EVA prep) referenced in NAS15-10110 Depress Pump Assembly Micron-A Technical Description and Operation Manual
  - 1.0 lbm Air residual Airlock depress gas loss
  - One of the currently limiting factors on ISS EVA tasks is whether the required On-Orbit Replaceable Units (ORU) or other equipment such as payloads can fit in the airlock with 2 suited crewmembers. The program is having to include whether there is room for ORUs in the airlock with the 2 crew in their priority decisions on what critical tasks get done.
  - EVA hatch is 36” x 40” diameter D hatch (XA has determined by analysis that pressurized EMU suit operations require at least a 35” pass-through).
- The larger equipment lock volume is 25.7 m^3 which provides secondary ingress capability, space for prebreathe and assistance from Intravehicular Activity (IVA) crewmembers during prep (supporting a waist entry suit) as well as equipment stowage and battery charge and stow locations
- Limited volume for in-flight suit maintenance
- Recharge of most suit consumables (does not recharge high pressure O2) Significant ground operations support for planning and procedures
- Infrequent EVAs

- No provision for dust mitigation
- ~14.7 psi with 21% O2 nominal atmosphere, can be brought down to 10.2 psi with 26.5% O2 (Reference In-Suit Light Exercise (ISLE) Prebreathe Protocol Peer Review Assessment", NASA Technical Memorandum, NASA/TM-2011-217062/Volume I, NESC-RP-10-00659 for further information)
  - 3 hours 10 minute prebreathe with In Suit Light Exercise (ISLE) shown in Figure 3.3 (minimal time at 10.2 pounds per square inch (psi)

The Phase V-5 Protocol consists of 60 minutes of O_2 on mask while performing EVA preparations followed by a 10.2-psi depress (light exercise at 5.8 ml·kg^{-1}·min^{-1}) on enriched air (0.265% O_2). This is followed by a 30-minute suit donning at 10.2 psi, and then 50 minutes of in-suit light activity (6.8 ml·kg^{-1}·min^{-1}), which is equivalent to walking a mile in 70 minutes, breathing O_2. It must be noted that this degree of exercise can be achieved with minimal effort. There is a final 50-minute in-suit prebreathe at rest, breathing O_2.

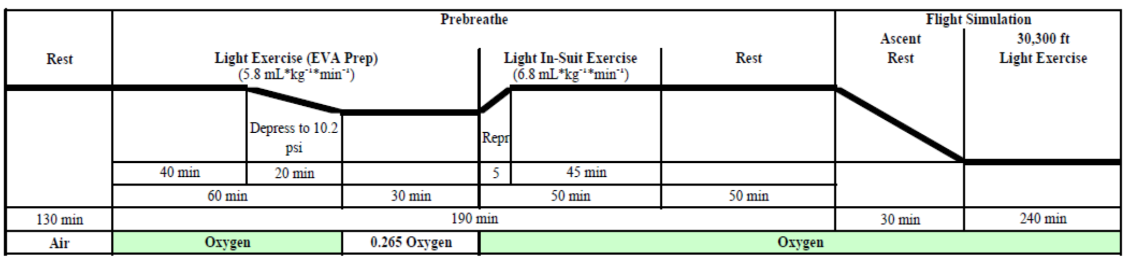


FIGURE 3.3 ISS ISLE PREBREATHE PROTOCOL

In addition to minimum suited pressurized EMU translation, based on previous EVA evaluations and on orbit demonstration, the translation corridor to transfer an unpressurized EMU is 31.5".

Assessing all known DRMs and with the current SoA in mind, the following challenges for exploration EVAs and ingress/egress methods beyond LEO were identified when considering proposed future capabilities:

- Suit Architecture
- Unassisted Don/Doff
- Recharge of all suit consumables (incl. high pressure O2)
- Volume for in-flight suit maintenance and spares
- Volume for donning/doffing and prebreathe
- Minimal consumables usage with vehicle ingress/egress cycles
- Increased crew autonomy for airlock operations
- Increased quantity and access of EVAs
- Alternative atmospheres for reduced prebreathe time
- Dust mitigation and Planetary Protection

Each of the challenges are expanded upon in the following sections and should be considered when evaluating the FOMs for an ingress/egress method.

3.1 SUIT ARCHITECTURE

Missions to destinations such as asteroids, Earth's Moon, and the Martian System are long duration missions resulting in needs that exceed current state-of-the-art EMU capability. For EVA, these Destination Classes are defined as follows:

- microgravity on a Engineered Surface (Spacecraft)
- microgravity on a natural surface, such as an asteroid or the moons of Mars
- partial gravity in a vacuum, such as the moon (lunar surface), and
- partial gravity in Partial Atmosphere, such as Mars surface

Reference EVA-EXP-0042 Exploration EVA System Concept of Operations for further definition of the Destination Classes as it relates to anticipated concept of operations for the suit.

The EMU was designed for the mobility required and the operational constraints present in a microgravity environment on a vehicle and is already performing beyond original specifications. The current EMU does not meet the reliability and maintainability requirements needed for missions beyond LEO and cannot be used as a surface/planetary exploration EVA suit due to lack of mobility for surface operations. Also, DRMs under consideration have assumptions that exceed the 25 EVA certification life of the ISS EMU, and these DRMs will have limited opportunities for resupply or maintenance. Available launch mass and volume will also be more constrained, so consumables and logistics must be minimized. The long duration missions also limit the EMU's ability to be upgraded to support the unique natural and induced environments envisioned for the multiple destinations. With all of this under consideration, mass, volume, Center of Gravity (CG), mobility, etc. should be as good as, or better than the EMU for a future suit. Interfaces with alternative ingress/egress concepts could change suit architecture.

3.2 UNASSISTED DON/DOFF

The EMU is a waist entry suit and is typically donned with the assistance of an IVA crewmember to help connect the lower torso assembly. Due to airlock architecture with the ISS environment at 1 atmosphere, the IVA crewmember who assists in EMU donning must also perform part of the prebreathe with the EVA crewmembers when the airlock is isolated from the general ISS volume, which is a significant crew time impact. A suit that is donned/doffed without assistance will reduce the EVA crewmember's time as well as eliminate the need for an assisting IVA crewmember's time. The EMU is a waist entry suit and can only be donned with the assistance of an IVA crewmember to help connect the lower torso assembly (reference Figure 3.2-1).

FIGURE 3.2-1 ISS CREW DONNING/DOFFING EMU

3.3 RECHARGE OF ALL SUIT CONSUMABLES

The three primary building blocks associated with an exploration EVA suit are the PLSS, the Suit/Pressure Garment, and the Power, Avionics, and Software system. Current EMU interfaces are similar to the needs of an Exploration Extravehicular Mobility Unit (xEMU). The following International Space Station (ISS) joint airlock Servicing, Performance, and Checkout Equipment (SPCE) hardware items (reference Figure 3.3-1) located in both the equipment lock and crew lock are designed to support Extravehicular Activities (EVAs) for the U.S. Extravehicular Mobility Unit (EMU) and Russian Orlan space suit:

- Battery Charger Assembly (BCA)
- Battery Stowage Assembly (BSA)
- EMU Don/Doff Assembly (EDDA)
- Umbilical Interface Assembly (UIA)
- Fluid Pumping Unit (FPU)
- Payload Water Reservoir (PWR)
- Power Supply Assembly (PSA)
- Metox Regenerator
- Metox Canisters
- Miscellaneous Maintenance Fixtures

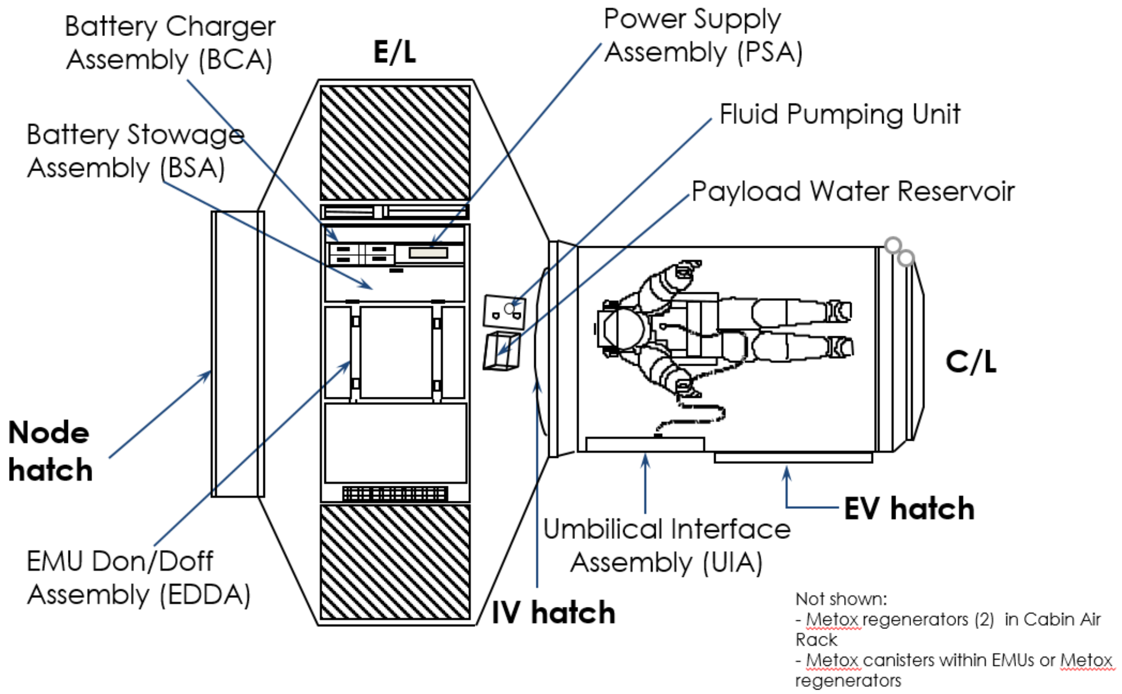


FIGURE 3.3-1 ISS JOINT QUEST AIRLOCK SPCE

3.4 VOLUME FOR IN-FLIGHT SUIT MAINTENANCE AND SPARES

The EMU was designed to be sent back down to the ground for most major suit maintenance at the end of a limited duration Space Shuttle mission. Because of this, the ISS Airlock (A/L) was not designed to facilitate every possible suit maintenance event that might occur. As transportation logistics evolved, workarounds arose out of necessity to include procedures to perform much more extensive suit maintenance tasks on the ISS than originally planned. As the crew explores further from earth, suit maintenance will have to be performed in-flight or at the destination, rather than relying on the luxury of transfer to the ground or transfer of tools.

3.5 VOLUME FOR DONNING/DOFFING AND PREBREATHE

Conventional airlocks have partnered with their host spacecraft to provide reasonable volume for EVA prep and post activities which include suit donning, doffing, and prebreathe. This has typically been solved in one of two ways. For relatively small spacecraft, such as the Gemini and Apollo capsules and the Apollo lunar lander, the entire habitable volume was used for these activities and depressurized as an airlock. Alternatively, spacecraft with much larger habitable volumes provided an intermediate partition such that the depressurizable airlock volume was minimized and kept separate from the rest of the spacecraft. This was done to minimize depressed consumables and interruptions to the rest of the vehicle's design and operation. On Shuttle, the middeck was used for most prep and post activities including partial donning and prebreathe whereas, on ISS, a shortened module called the Equipment Lock was added which provided bulkheads and storage space in between the airlock and the rest of ISS. This is comparable in EVA prep and post function to the Shuttle middeck. Regardless of stack size, future EVA systems must provide accommodations for don/doff and prebreathe activities in some way or another.

3.6 MINIMAL CONSUMABLES USAGE WITH VEHICLE INGRESS/EGRESS CYCLES

In order to transition from cabin pressure to the exterior environment, cabin atmosphere must somehow be displaced. Some architectures, such as small capsules, have chosen to vent the entire volume of the cabin directly overboard. Others have attempted to conserve resources using reclamation pumps. Even with minimized volumes and relatively high efficiency pumps, some amount of atmosphere is still lost overboard during each ingress/egress cycle. Exploration architectures with high numbers of EVAs thus may pay a non-trivial penalty for the accumulated mass lost in many cycles. As an example, see Appendix D for current SoA consumables via ISS A/L actuals.

3.7 INCREASED CREW AUTONOMY FOR AIRLOCK OPERATIONS

Exploration architectures with increased communications delays from earth-based support teams will face challenges conventionally addressed through low-latency communications. Items as simple as assisting crew with procedures during airlock operations will need to be addressed in new ways. Though this may include increased reliance on IV support crewmembers as has been demonstrated on ISS, automation of many functions may also be necessary in order to contain crew workload to a manageable level. Airlock architecture choices will likely dramatically sway the level of manual and autonomous features necessary to increase crew autonomy.

3.8 INCREASED QUANTITY AND ACCESS OF EVAs (HARDWARE CYCLE LIFE AND OPERATIONS)

Significant effort has historically been needed to ensure safe EVA operations. For spacecraft maintenance EVAs, this is reasonably acceptable due to the relatively infrequent nature of vehicle failures and planned nature of nominal construction and reconfiguration events. However, human spaceflight systems that seek to explore and pioneer unknown natural surfaces may be hampered without increased quantities and access to EVA.

3.9 ALTERNATIVE ATMOSPHERES FOR REDUCED PREBREATHE TIME

A fundamental limitation of human physiology is the potential for acute and chronic injury due to Decompression Sickness (DCS). Because of compromises associated with suited mobility, conventional EVA systems have operated at pressures reduced from that which human beings live at long term. Even with the short duration of the EVA event, it is necessary to intentionally control the transition from the habitable volume's saturation atmosphere to that which the EVA suit will run on. Unfortunately, the amount of time necessary to make this transition is directly proportional to the difference between vehicle saturation and EVA pressures. This amount of time can be non-trivial compared to the duration of the EVA itself and is a significant barrier to EVA availability because of crew time penalties. If EVA suit design and ops cons cannot allow for increased EVA suit pressure, the only other known way to reduce the pressure differential is to decrease the nominal vehicle pressure and determine a minimal denitrogenation strategy that allows for on-demand EVA capabilities. This would require alternative atmospheric blends, the more dramatic of which may pose non-trivial issues including new Human Health uncertainties and vehicle design challenges such as reduced effectiveness for atmosphere-based avionics cooling.

3.10 DUST MITIGATION AND PLANETARY PROTECTION

Dust mitigation and resistance to abrasion poses a significant technical challenge for many exploration DRMs. Dust can damage suit components and may become a crew health hazard if introduced into the crew cabin in sufficient quantities. In addition to the basic mechanical design challenge, airlocks provide a significant opportunity of controlling or propagating backward and forward contamination. As such, planetary protection concerns for human health and science quality partner with engineering design at the airlock interface between EVA and the spacecraft. Past methods of ingress/egress would have the crewmember traversing/translating directly through the dust that was brought in after an EVA both after the crewmembers doff their suits and prior to donning their suits. This feature alone poses a significant challenge for ingress/egress methods. "The point at which the dust becomes the greatest threat to safety is in the donning and doffing of the space suit, ingress and egress of the EVA airlock." (Cohen, M. 2000).

4.0 CONCEPTUAL SOLUTIONS

NASA headquarters chartered the Human Exploration Architecture Team (HAT) in 2012, which was tasked with examining a flexible path for human exploration and refining the notional DRMs, identifying core capabilities and common architectural elements needed to support manned missions to multiple destinations (reference Figure 4-1).

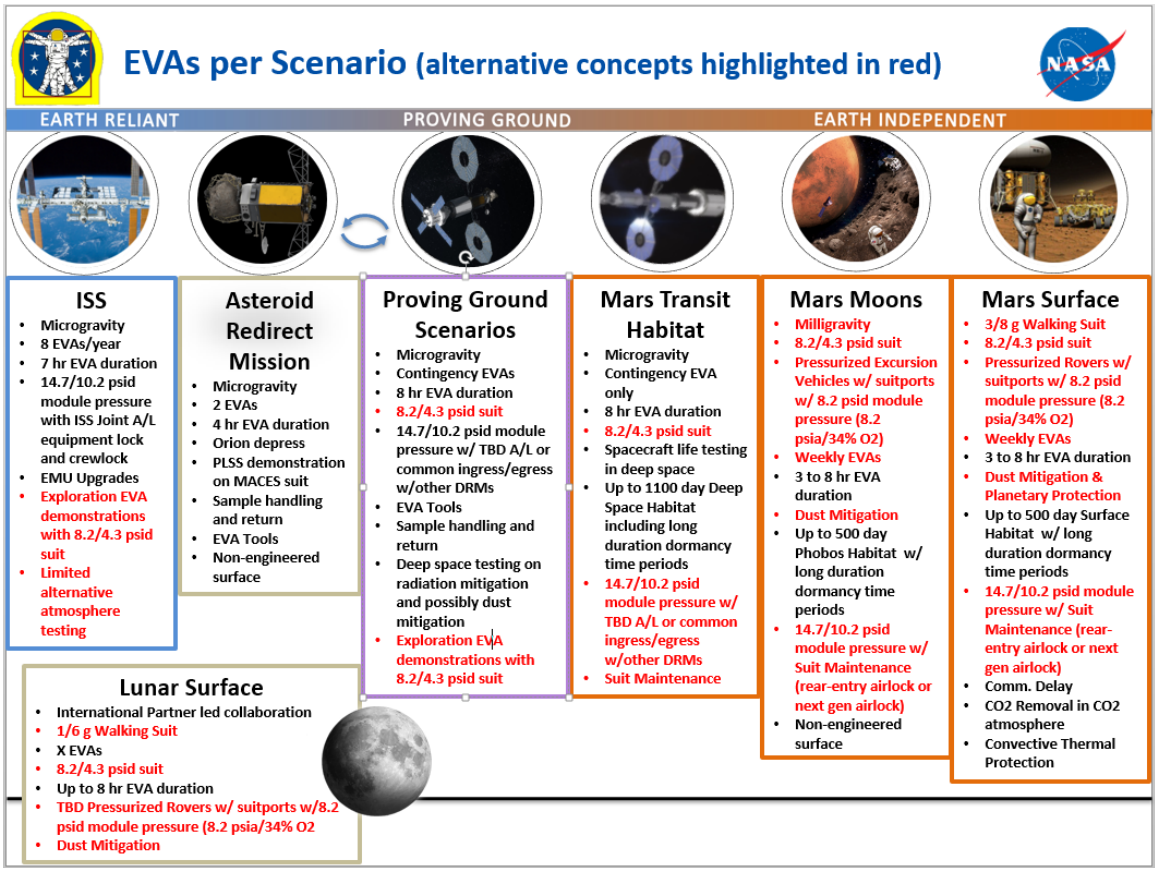


FIGURE 4-1 SCENARIOS INCORPORATING ALTERNATIVE CONCEPTS

Through HAT, exploration EVA development was identified as one of the top five capabilities required for enabling missions to multiple destinations for tasks ranging from spacecraft assembly through maintenance and repair of satellites and vehicles to conducting exploration science at natural destinations. This prioritization and early need was based on the significant interplay exploration EVA systems have with several of the other possible transportation and destination elements.

Many of the conceived DRMs for human exploration are EVA-centric upon arrival at the destination and include science-focused EVAs that increase EVA frequency and require a paradigm shift from heritage programs. For these heritage programs, NASA has used tightly-controlled and highly-scripted EVA timelines at a relatively low annual rate (about 8 EVAs/year on average in the ISS Program) and relied heavily on interaction between the EVA crew and ground team. For exploration missions, a flexible operational paradigm is needed so that the crew can make changes to their activities in near real-time to satisfy science and maintenance objectives. Such EVA-centric missions are theorized to require a capability that is both reliable and robust while accomplishing 3 to 6 EVAs per week of shorter duration than the construction-focused missions of Shuttle and ISS, while maintaining the flexibility to perform long duration EVAs when necessary.

The following sections will discuss the details of multiple systems; such as a rear-entry airlock, suitport, and suitport-airlock (suitport in an airlock) configurations that an exploration EVA suit may interface with during ingress/egress. Operational concepts for some of these systems and how they are applied to specific DRMs are documented in EVA-EXP-0042, EVA Office Exploration EVA Capabilities and Operational Concepts Document.

4.1 SUITPORT CONCEPT

The suitport concept (generally assumed to be on pressurized rovers) allows for a 15 minute prebreathe when partnered with a reduced saturation pressure vehicle atmosphere. This architecture increases the feasibility of frequent EVAs, and minimization of the amount of dust that gets inside the cabin where the crew lives. An exploration EVA suit would include a Suitport Interface Plate (SIP) in order to interface with a suitport as shown in Figure 4.1-1. The following figure shows a notional suitport interface plate (green) on a suit:

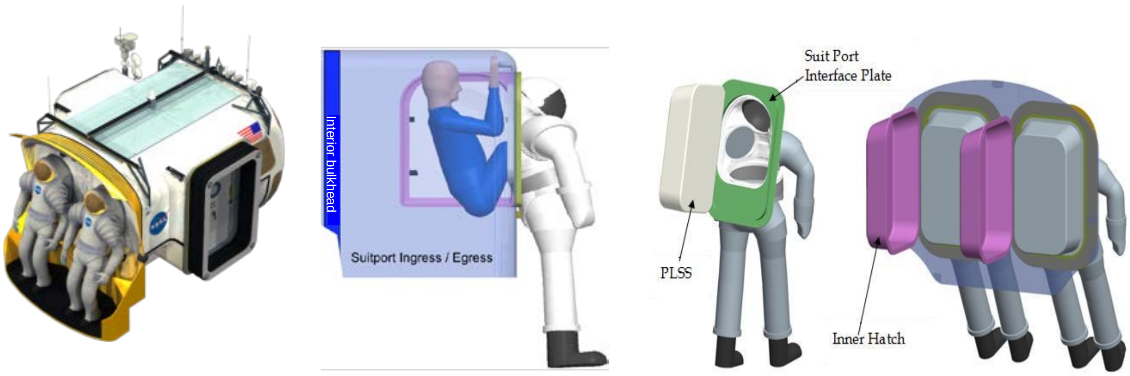


FIGURE 4.1-1 SUITPORT INTERFACE PLATE

A suitport includes two pressure sealing interfaces, one between the SIP (shown in green on the suit) and the outside of the bulkhead and another between the inner vestibule hatch (shown in purple) and the inside of the bulkhead in the habitable volume of a host vehicle (reference Figure 4.1-2).

FIGURE 4.1-2 SUIT INTERFACING TO SUITPORT

Suits are attached to the bulkhead via the SIP attached to the suit. The SIP creates a sealing interface with the bulkhead such that the bulkhead vestibule hatch can be open to the cabin and the PLSS hatch can be open to the cabin, while the opposite side of the bulkhead and front of the suit are at vacuum. The outside of the suits are not accessible for maintenance nor sizing while on suitport. The vestibule hatch is also a sealing interface. While the suitport vestibule hatches are open, the exploration suit SIP acts as the pressure barrier between the habitable volume and vacuum. The volume around the suits is continuously at vacuum/surface atmosphere while the inside of the suit remains at 0.9 (pounds per square inch delta (psid) when not in use to maintain thermal conditioning of the suit, to inhibit the migration of dust into the suit, and to minimize leakage (some low level leakage is expected). When the suit is not docked to the suitport, the suitport vestibule hatch (inner hatch/vestibule door) separates the internal habitable volume from vacuum. Sample transfer could be performed through a Suitport Transfer Module (SPTM). Depending on the design of the suitport, the seal interface between the suit and the vestibule may require an EVA to perform maintenance or repair in the case that the seal become damaged/contaminated.

The suit is assumed to be at 8.2 psid during prebreathe, donning/doffing, and part of the suit checkout. EVA suit design for nominal operation at a delta pressure of 8.2 psid is known to be feasible (nominally operated at 4.3 psid during the EVA) thus suitports can be used if the pressurized cabin can be reduced to 8.2 (pounds per square inch absolute) (psia). Vehicle/cabin pressure must be brought down to 8.2 psid or less in order to ingress the suit without blowing it out. Prior to an EVA, the suit must be brought up to cabin pressure and equalized with the vestibule and the cabin. The crewmember ingresses the suit unassisted through the suitport (which necessitates a rear entry suit), closes the suit/PLSS hatch, closes the vestibule hatch, and depresses the vestibule volume between the hatch and the PLSS.

The exploration atmosphere of 8.2 psi/34% O2 enables a significantly shorter prebreathe when compared to traditional airlocks operating at 14.7 psia and at 10.2 psia, and from 21-28% O2, depending on the prebreathe protocol. This would be conducted while the crewmember also performs suit leak checks. While models have been used to develop a preliminary prebreathe protocol using the exploration atmosphere (Abercromby et al., 2015), that protocol has not yet been validated through ground trials. Vehicle atmospheres higher than 8.2 psia would likely require additional features in order to maintain the maximum delta pressure across the suit during ingress/egress, thus emphasizing the value of further investigation in reduced pressure vehicle atmospheres.

Also, it should be noted that surface operations features on the exterior of the suitport concept would be required to restrain suit components such as legs, boots, arms, and gloves during driving. This is necessary to reduce inadvertent cycling, abrasion and impacts induced through vehicle motion. Overall, suits are envisioned to be protected by an environmental cover as shown in Figure 4.1-3

FIGURE 4.1-3 SUITPORT CONCEPT IN PRESSURIZED ROVER WITH ENVIRONMENTAL COVER

Dust mitigation is maximized greatly compared to a conventional A/L by keeping the dustiest parts of the suits on the outside of the cabin and thus decreasing exposure of the habitable volume to dust, particulates, or other harmful materials. However, dust exposure is not completely eliminated so a dust defense plan must be in place to mitigate dust entrance into the cabin (as discussed later in this document). The intent of suitport is to allow for more rapid egress and ingress of an exploration vehicle while limiting the amount of dust entry into the cabin and reducing consumables. This new technology will result in reduced gas loss over standard airlock operations. Gas used would include the gas leaking from the suits for the duration the suits are on the suitport (at 0.9 psid), the gas used to bring the vestibule volume and the suit up to cabin atmosphere (8.2 psia) to allow the crewmember to ingress the suit, and the gas used post EVA to increase the vestibule volume and the free volume around the crewmember inside the suit from 4.3 psid to 8.2 psia.

Suitport Benefits
• Reduced Gas Loss • Decreased exposure of habitable volume to dust & particulates • Rapid Ingress/Egress

It is anticipated that matured versions of suitport-compatible exploration EVA suits will not preclude operation in a typical airlock (including ISS Joint Airlock) but will allow for operation in multiple airlock, suitport, and/or hybrid suitport-airlock configurations.

Early stage suitport development and testing in JSC Chamber B proved the feasibility (Figure 4.1-4) of the suitport concept as discussed further in Section 5.3 Suitport Testing. An exploration EVA suit can be designed and scarred built to eventually be compatible for possible future development of suitport capability; however, to fully designate the suit as suitport-compatible a functioning suitport will be required for testing and certification. Suitport compatibility includes the following: rear-entry

Suitport Challenges
• Additional on-back mass • PLSS Outer Mold Line (OML)/plumbing • Environment exposure, delta pressure exposure, material degradation • Suit don/doff difficulty

don/doff capability, the addition of a SIP, mobility taking into consideration the mass and CG of the SIP, volumetrically constrained PLSS packaging, plumbing and routing designed with the SIP installed, and suit durability/mobility that can withstand a constant delta pressure. The port on the suit that allows access to vacuum during EVAs and while on suitport should be compatible with a vacuum umbilical interface in order not to preclude use in an airlock or a suitlock-airlock (suitports within a pressurizable volume).

FIGURE 4.1-4 SUITPORT TESTING IN CHAMBER B

While the suitport concept works well with a pressurized rover, long duration human stays in excess of a few days must provide a pressurized volume large enough to allow the crewmembers to bring the suits inside. It is assumed this function will reside on a habitat and will allow for regular suit maintenance, suit resizing, suit swapping for crew changeout, and suit swapping for suit end of life (conservatively, about 2 suits per crewmember over a 500 day mission duration with maximum EVA hours).

4.2 REAR-ENTRY AIRLOCKS

The Rear-Entry Airlock (which has sometimes been referred to as a “Suitlock”) looks similar in concept to suitport (Figure 4.2-1), except that the suit does not act as a pressure sealing interface to the bulkhead and vehicle. Instead, there is one internal hatch to access the airlock chamber and two bulkhead suit access hatches. The only pressure sealing interfaces are the hatches themselves. Similar to the suitport, the crew dons/doffs their suits through the bulkhead. The volume around the suits is pressurizable and would be pressurized during suit don/doff operations while the hatches are open to the cabin. The EVA suits are at ambient pressure (no delta pressure across the suit) inside the rear-entry airlock. The suits are not stowed in vacuum between EVAs as they are while on the suitport concept.

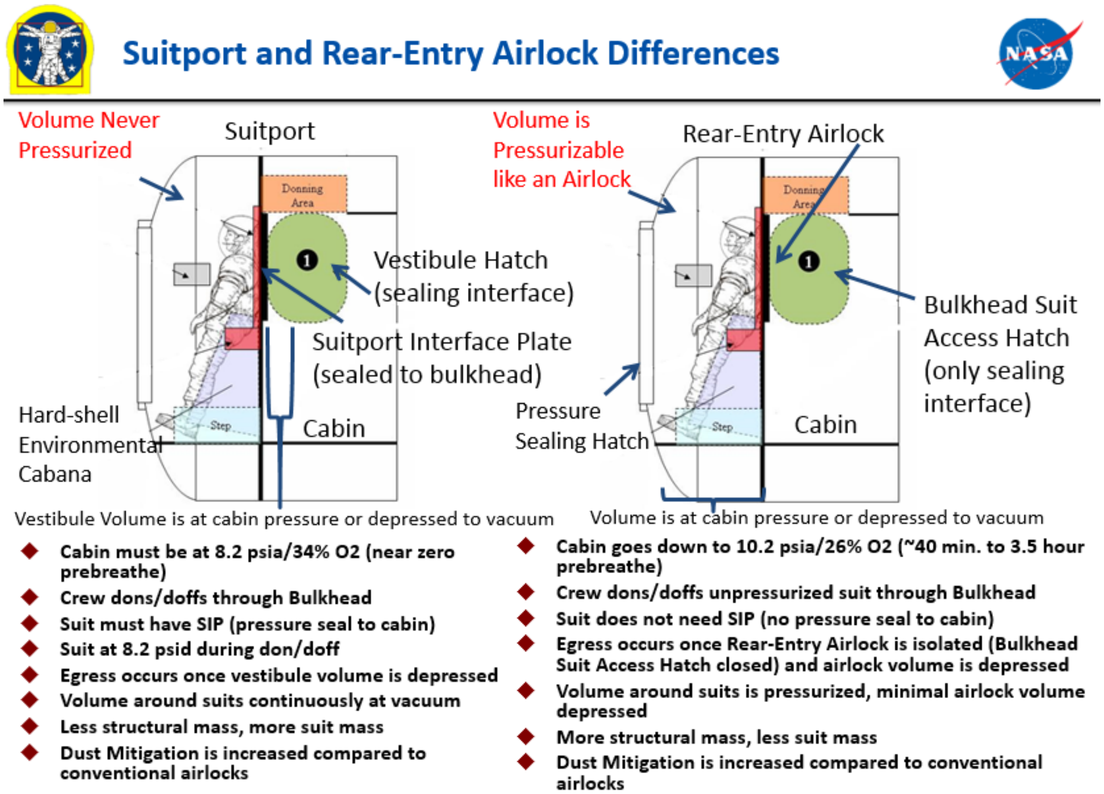


FIGURE 4.2-1 SUITPORT AND REAR-ENTRY AIRLOCK DIFFERENCES

The rear-entry airlock has bulkhead suit access hatches on the bulkhead that allow for rear-entry into suits that are contained inside the airlock chamber. In addition to the two bulkhead suit access hatches, there is an internal hatch (reference Figure 4.2-2) that allows the crew to ingress the airlock while at IVA pressure for maintenance.

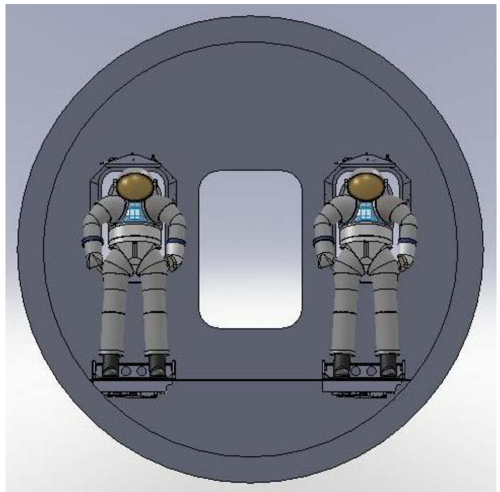


FIGURE 4.2-2 INTERNAL HATCH (OPEN)

As mentioned, since the suit interface to the bulkhead itself is *not* hermetic, the volume around the suits must remain pressurized in order to open the bulkhead suit access hatches and ingress the suits. Thus, all three hatches to the cabin must be sealed prior to depressurizing the airlock chamber. Egress occurs once the rear-entry airlock chamber is isolated (bulkhead suit access hatches and internal hatch sealed) and is depressed. Gas can be reclaimed depending on filtration requirements/contamination.

Because of this arrangement, the Rear-Entry Airlock concept is more similar to a traditional airlock than it is to a Suitport (reference Figure 4.2-3). The rear-entry airlock does not require the habitable volume behind the suits to reduce to 8.2 psid like a suitport so as not to blow the suits out. The only significant difference is that, assuming a rear-entry suit, the donning hardware is integrated into the bulkhead of the airlock. With the addition of the pressure-sealing hatches, this essentially places the suits inside a conventional airlock albeit having donned them "through the wall" prior to closing the hatch over the rear-entry PLSS to truly isolate the airlock from the rest of the vehicle. For this reason, the Rear Entry Airlock concept can look very similar to a Suitport. A rear-entry airlock does not require a SIP. The Rear-Entry Airlock allows access to suits for maintenance, inspection, cleaning and addresses dust contamination concerns by allowing the crewmembers to don Personal Protection Equipment (PPE) prior to ingressing at IVA pressure through the internal hatch. With a rear-entry airlock on a habitat, the crew can clean the suits before bringing them into a maintenance workstation, or they can perform maintenance in front of the suits with enough volume as discussed in Section 7.2.8.2 Suit Maintenance.

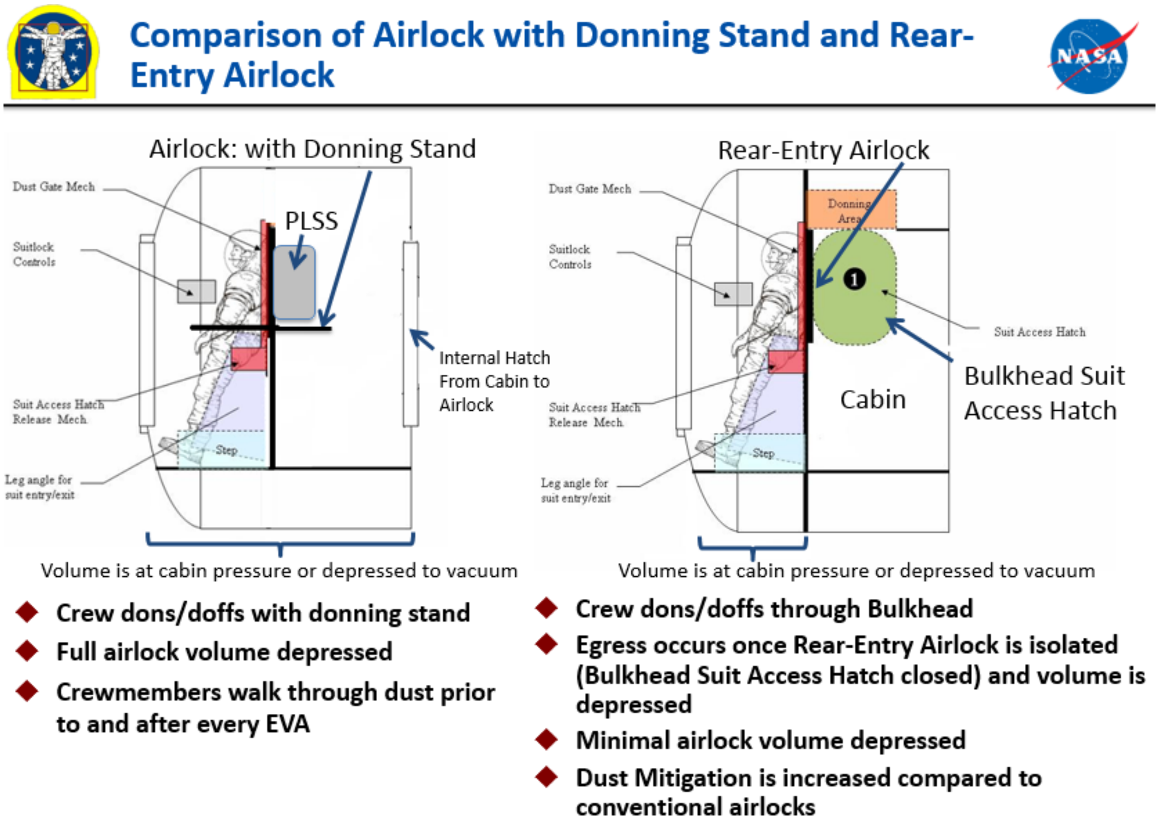


FIGURE 4.2-3 REGULAR AIRLOCK VS. REAR-ENTRY AIRLOCK CONCEPT

The rear-entry airlock provides similar dust mitigation and contamination protection as the Suitport, though without a true hermetic seal it is not assumed to be truly equal and may require additional mitigation features to fully break contamination chains and ensure human health. Despite this, dust mitigation is increased beyond regular airlock capabilities since the crewmembers are not walking directly through the dust as they would in a regular airlock.

4.3 SUITPORT-AIRLOCK

The suitport-airlock concept incorporates suitports into a pressurizable volume and combines the benefits of the previously described Suitport and Rear-Entry Airlock concepts. Suitport-airlocks are suitports on the bulkhead that access an airlock and includes an internal hatch (either around a suitport or in between the suitport hatches). The volume around the suits can be left depressurized to vacuum that acts purely as a suitport to allow for quicker EVA egress/ingress, held at a delta pressure to decrease suit leakage during unmanned quiescent mode, or be pressurized to operate as an airlock at the same pressure as the habitat, which allows shirtsleeve access to suits for maintenance, suit swapping, sterilization, and transfer of equipment. The difference between a rear-entry airlock (suitlock) and suitport-airlock are shown in Figure 4.3-1. The dust mitigation for a suitport-airlock is the same as for a suitport. If it needs to be stricter, you treat it as a suitport. If you have to access the outside of the suits, it's the same dust risk as having to bring the suits in from a suitport to maintain them.

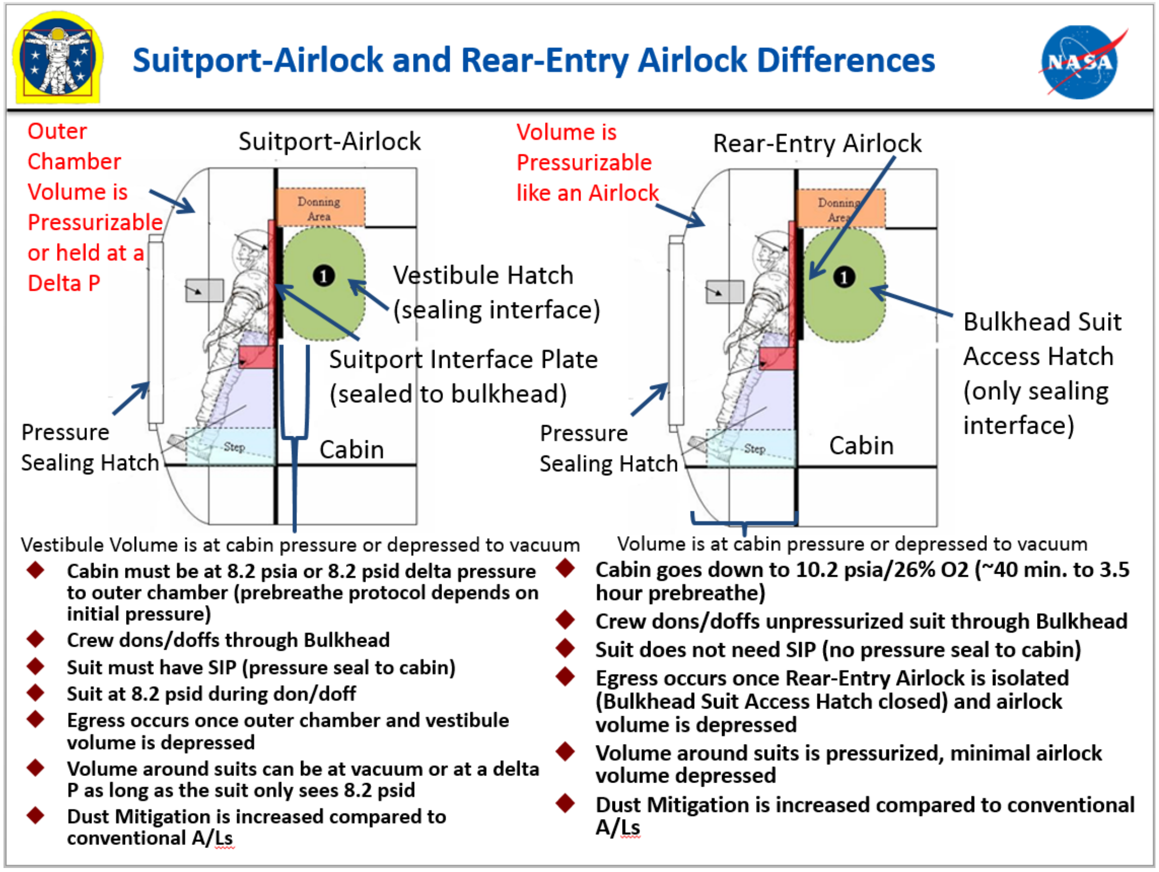


FIGURE 4.3-1 SUITPORT-AIRLOCK VS. REAR-ENTRY AIRLOCK CONCEPT

A suitport-airlock can be incorporated into an asset that can be brought down to ~8.2 psia with 34% O2 in preparation for EVA and during suit donning and doffing operations. The cabin must be kept at 8.2 psia while EVA suits are on the suitports (to limit pressure differential across the suit); however, it could be possible to operate the chamber around the suits at a slight pressure to make up the difference and allow use of a suitport-airlock on a habitat or pressurized rover that goes above 8.2 psid. The suit could be kept at a delta pressure with a suitport-airlock, such that the outer chamber is at 2 psia and the cabin is at 10.2 psia causing an 8.2 psid. These details have not been examined in full yet, but if successfully analyzed and implemented this could be valuable for nominal EVAs from a habitat. It could also be an important mitigation step for use on suitports if on-orbit suitport testing cannot be accomplished prior to use for the first time in the Mars vicinity (i.e. if difficulty or contingency with the suitport, the outer chamber can be repressed).

The suitport vestibule is regulated by the vehicle during unsuited ops (i.e., traverse, etc.) for suit stowage. The cabin does not need to be depressed in order to perform EVA out of another hatch to translate suits onto the suitports since an internal hatch is included similar to the rear-entry airlock (hatch around or between suitport hatches). Sample transfer could be performed through a Suitport Transfer Module (SPTM) or an internal hatch depending on if the outer chamber is pressurized or not.

An EVA can be started with the outer chamber still pressurized (rear-entry airlock mode) or unpressurized (in suitport mode). Figure 4.3-2 shows another rendering of a suitport-airlock concept on a habitat.

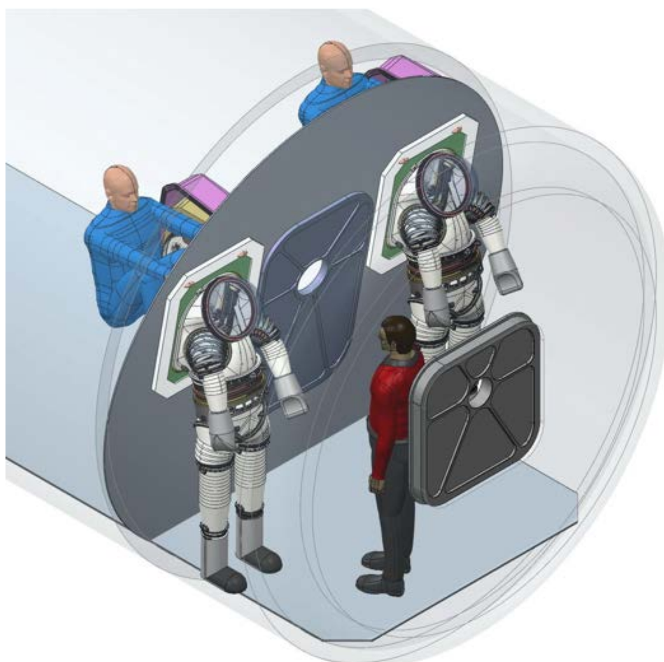


FIGURE 4.3-2 SUITPORT AIRLOCK CONCEPT

5.0 PAST TRADE STUDIES

Many different style airlocks have been used in the past as shown in the Appendices. These styles ranged from depressurizing the capsule (as in the Apollo lunar missions), to inflatables, to small airlocks, and included additional chambers necessary for prebreathe and maintenance. When discussing challenges for reduced prebreathe, dust mitigation, and pressurized rover interfaces, alternative solutions began emerging through Cohen et al. at the NASA Ames Research Center in the late 1980s. First patented in 1989 (lapsed), the suitport concept (Cohen, M. 1987) on pressurized rovers initially began as an interface to a hard suit. Early concepts showed potential for Hazmat application and routine space station operations, postulating substantial savings in atmosphere loss, crew time, power, pump cooling, and contamination isolation (Cohen, M. 1995). Further studies discussed minimum volume airlocks, “airlockless airlocks”, and pressurized rover concept design approaches (Cohen, M. 2000).

Another significant discussion in the Cohen papers included the following discourse:

“Pressurized surface rovers present their own issues of docking, but they differ from orbital systems in the degree to which they interact with the design of the habitats or EVA support modules to which they must connect. The key question is whether the EVA airlock can double as the docking port between the mobile vehicle and the habitat. Perhaps the most salient point on this question is the lesson from Skylab: that the design should not situate the airlock between the vehicle and the habitat, which in Skylab were the Apollo Command Module and the Saturn Orbital Workshop. The consequence was that whenever two Skylab crew members went EVA and depressurized the airlock, the third needed to retreat in advance to the Apollo Command Module, lest he be cut off from escape by the depressurized airlock.” (Cohen, 1983 & Cohen, 1985)

“The lesson from Skylab is that the crew should not enter the escape vehicle through the airlock from the crew habitat applies equally to the design of EVA airlocks as it does to the design of docking ports. Although it is tempting to “economize” by combining the two functions of docking port and airlock, it is a false economy. Combining the airlock and the docking port into a single unit compromises the functioning of both, to the benefit of neither.” (Cohen, 2000)

The advanced airlock initiative was deferred when it was decided to continue using the EMU for the ISS. Some of the same questions originally highlighted in the Cohen papers are extended here. Since the Constellation Program, alternative airlocks have been assessed in trade studies and incorporated in mockups for limited feasibility testing.

The Desert Research and Technology Studies (DRATS) team began using a mockup of the suitport during the Constellation Program in 2008 (Romig, B., et al. 2009). The Airlock Suitlock Suit Port Assessment Team (ASPAT) was formed in 2008 to determine appropriate ingress/egress methods for pressurized rover and habitat during CxP for lunar surface destinations. The team assessed mass, power, consumables, time, effect of concept design on EVA system, etc.

In order to address some of the issues and to advance the concept, the Advanced Exploration Systems (AES) Suitport Project was started in Fiscal Year (FY) 12 with a focus on system design. Development and testing occurred before the Suitport Project funding ended for FY13, concluding with the early stage suitport demonstration test discussed in Section 4.1.

The Exploration Atmospheres Working Group was formulated in 2005 and again in 2011 to select the best combination of pressure and oxygen and the associated forward work.

The Near Term DRM Quick Study was performed by the EVA Office in conjunction with Engineering Directorate in 2014 to determine if the suitport concept should be considered within "near-term" DRMs (2021-2033). The study looked at a proposed module that would go both to the ISS and a Lunar Distant Retrograde Orbit (LDRO) and determined that the suitport-airlock is the ingress/egress method that should be tested on this module. Discussions on whether testing on-orbit is prudent are still ongoing; however, the current stance is that it is not a requirement prior to going to Mars, but needs further ground testing to determine a path forward.

The Small Habitat Commonality Team was established in 2014 to look into possible commonality between certain assets to help reduce cost. This included understanding which modules included EVA capability and options for ingress/egress commonality.

The following sections examine the crosslinks and implications of these studies in further detail.

5.1 DRATS

DRATS used analog testing to evaluate technology, human-robotic systems, and EVA equipment for future human exploration missions. These simulated missions helped to assess conceptual design, potential technology, and operations. The 2008 field tests for a pressurized rover concept was held at the Black Point Lava Flow in Arizona to gather data on the suitport concept and compare the scientific productivity and human factors during a 1-day exploration, mapping, and traverse mission versus utilizing an unpressurized rover prototype.

Human factors data was collected on human exertion, discomfort, fatigue, suitport operations, handholds, and volume (Romig, B., et al. 2009) and was found to be acceptable and provided lessons learned for future designs. Quantitative assessment of crew productivity by an on-site team of expert field geologists found that compared with unpressurized rover traverses, the same crewmembers were 57% more productive during pressurized rover traverses and used 61% less EVA time due to the ability to use EVA only when required by utilizing the visibility from inside the Small Pressurized Rover (SPR) combined with the ability to rapidly egress and ingress the SPR via suit ports. Further conclusions indicate that the travel distance of an unpressurized rover is constrained by the 8 hour consumables limit among other observations (Abercromby, A., et al. 2010).

The 2009 field test pressurized rover concept incorporated the suit environmental enclosure, or “cabana”, to protect the suits from dust during the field test (Abercromby, A., et al. 2012). 2009 also marked the last year DRATS investigated partial gravity EVA surface ops within the context of the CxP program.

In 2010, the DRATS field test expanded upon previous investigations by incorporating two pressurized rovers as Multi-Mission Space Exploration Vehicles (MMSEV) over a 14 day mission (Abercromby, A., et al. 2013), but transitioned to simulating microgravity operations concepts appropriate for Near Earth Asteroid missions. This included renewed focus on a modular vehicle design that could be configured for microgravity or partial gravity destinations (Figure 5.1-1).

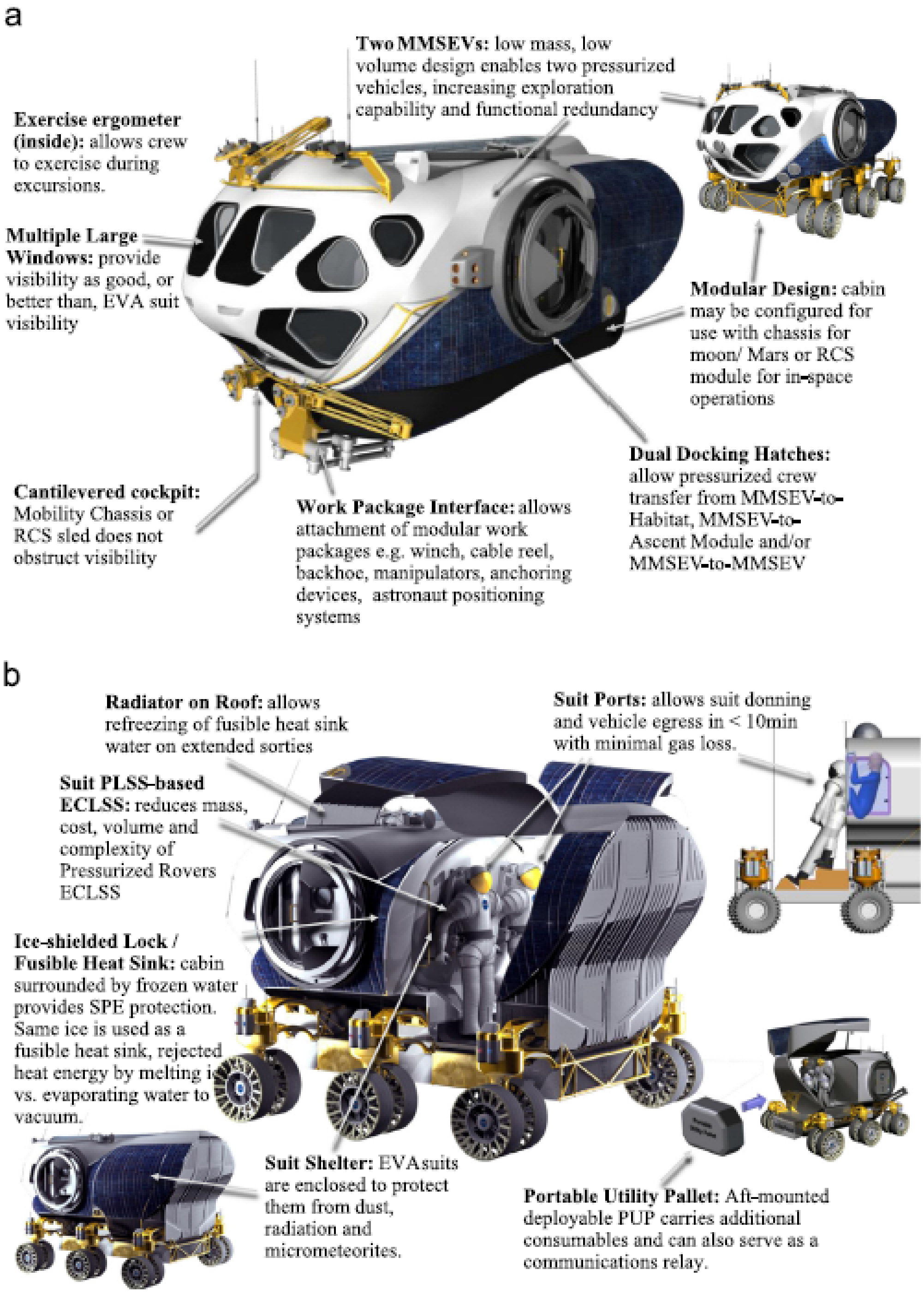


FIGURE 5.1-1 MODULAR MULTI-MISSION SPACE EXPLORATION VEHICLE

The following bullets indicate which challenges (as identified in Section 3) have been addressed to some extent in this study:

- Suit Architecture: Yes

- Unassisted Don/Doff: Yes (unpressurized)
- Recharge of all suit consumables (incl. high pressure O2): No
- Volume for donning/doffing and prebreathe: Yes
- Minimal consumables usage with vehicle ingress/egress cycles: Yes
- Increased crew autonomy for airlock operations: Yes
- Increased quantity and access of EVAs: Yes
- Alternative atmospheres for reduced prebreathe time: (Alternative atmosphere was assumed, not evaluated)
- Volume for in-flight suit maintenance and spares: No
- Dust mitigation and Planetary Protection: Yes

5.2 AIRLOCK SUITLOCK SUIT PORT ASSESSMENT TEAM (ASPAT)

ASPAT was started in 2008 to determine appropriate ingress/egress methods for a pressurized rover and habitat during CxP (destination moon) to address suit challenges and overall mission benefits. Over the course of the study, many alternate concepts were examined with several concepts selected to be considered within scope for a pressurized rover and a habitat on the lunar surface. The study involved significant participation time over the next year and a half, along with cost due to additional resources deployed to properly assess overall lunar mission manifest mass, power, consumables, time, safety, and effect of concept design on the EVA system. Independently from the Cohen paper (Cohen, M. 2000), the ASPAT team also determined that the conformal, single person "coffin" designs or single person chambers were unsafe due to a fundamental difference in utilizing the buddy system during a two person EVA. Ground rules and assumptions are included in the final report along with analyses and results. It was determined that the pressurized rover traverse distances would be too constrained to have to carry the extra mass, power, and consumables for concepts other than the suitport. ASPAT and analogs have shown suitport to be preferred on pressurized rovers for multiple reasons, such as lower mass, power, and volume and therefore, greater drive distance. Suit challenges due to suitport would have to be looked into further through testing. The following concepts were chosen for the pressurized rover and the habitat:

Suit Challenges
Additional on-back mass
PLSS Outer Mold Line (OML)/plumbing
Environment exposure, delta pressure exposure, material degradation
Suit don/doff difficulty

- Finding 1: Pressurized rover – suitport
- Finding 2: Habitat – rear-entry airlock (called "suitlock" in the ASPAT report)

The following bullets indicate which challenges (as identified in Section 3) have been addressed to some extent in this study:

- Suit Architecture: Yes
- Unassisted Don/Doff: No
- Recharge of all suit consumables (incl. high pressure O2): Yes
- Volume for donning/doffing and prebreathe: Yes
- Minimal consumables usage with vehicle ingress/egress cycles: Yes
- Increased crew autonomy for airlock operations: Yes
- Increased quantity and access of EVAs: Yes
- Alternative atmospheres for reduced prebreathe time: Yes
- Volume for in-flight suit maintenance and spares: Yes
- Dust mitigation and Planetary Protection: Yes

5.3 SUITPORT TESTING

Suitport feasibility testing was performed by the Crew and Thermal Systems Division (CTSD) using the Johnson Space Center Building 32 Vacuum Chamber B and the Z1 prototype space suit with an 8.3 psi differential across the space suit. The Z1 suit is a rear-entry suit with soft upper and lower torso with bearings for mobility and includes a SIP to interface with the suitport designed for the chamber. Design challenges and work-arounds and/or solutions are discussed in an initial paper such as aspects of the suit (PLSS and SIP shapes, glove and boot adjustment), the donning angle of the suit, alignment guides and suitport mechanisms describing the test (Boyle, et al. 2012). The suitport mechanisms (such as the second generation Marman Clamp and the Pneumatic Flipper), were tested in Building 32 Chamber B along with other design solutions in the first ever human-in-the-loop test of 8.3 psid pressurized donning with a suitport compatible prototype suit. The paper describes the suit, suitport mechanisms, chamber layout and systems, don/doff aids, and results.

The test found that some test subjects could not don, or were partially donned and unable to doff, the suit until the chamber was repressurized. During donning, some crewmembers were unable to don the suits due to difficulty getting the foot past the knee break in the suit due to the pressure differential. The introduction of a don/doff aid helped; however, this illustrated that further improvements need to be made and testing of suitports need to be further demonstrated in 1-g conditions (pressurized donning/doffing, the use of don/doff aids, etc.). Doffing also proved to be difficult due to bladder fold and ankle and knee joints and the need for leverage to get their upper body out of the suit. Microgravity could help with doffing, but may further impede donning. Scores based on the Modified Cooper-Harper Scale showed improvement after several dockings/undockings from the suitports, which indicates operational experience and crewmember technique are valuable. These could prove to be quite different between 1g and microgravity due to the extent of the differences between gravities and how reduced gravity affects don/doff. Testing in reduced gravity environments would help identify any currently unknown issues. Continued testing is needed for system maturation (Boyle, et al. 2013):

"This design test effort has significantly improved the technology readiness level of the suitport, taking it from the concept stage, to a demonstrated prototype in ground testing. The next step, when funding and appropriate missions are identified is to implement suitport in a human vacuum chamber test with the chamber at space vacuum conditions, followed by thermal vacuum testing with a prototype space suit and life support system."

The following bullets indicate which challenges (as identified in Section 3) have been addressed to some extent in this study:

- Suit Architecture: Yes
- Unassisted Don/Doff: Yes
- Recharge of all suit consumables (incl. high pressure O2): No
- Volume for donning/doffing and prebreathe: No
- Minimal consumables usage with vehicle ingress/egress cycles: No
- Increased crew autonomy for airlock operations: No
- Increased quantity and access of EVAs: Yes
- Alternative atmospheres for reduced prebreathe time: No
- Volume for in-flight suit maintenance and spares: No
- Dust mitigation and Planetary Protection: (assumed to be addressed by the design concept; not explicitly studied)

5.4 RAPID EVE METHODS PHASE 1: NEAR TERM DRM QUICK STUDY

The Rapid EVA Methods (REM) study was a large trade study that would have assessed the ingress/egress methods for all exploration vehicle assets and DRMs. The first phase of the study incorporated knowledge gained during past suitport testing and incorporated recommendations from ASPAT (with a focus on commonality and Mars extensibility). The EVA Office determined that further integration was required that would take into consideration the following:

- Tasks/actions coming from Destination Operations Team (DOT) for the Evolvable Mars Campaign (EMC) including Cislunar and Mars assumptions and conops (2014-2016)
- Exploration Augmentation Module (EAM) project kickoff (ISS and LDRO) requirements working groups (2014-2015)
- SMT Gap Closure #401 Ingress/Egress Trade Study input
- Exploration EVA suit technology development (suitport compatibility requirements under consideration, but no current funding for suitport)

- Schedule constraints to determine what should be tested on ISS with current extension to 2024 and potential 2028 extension

The study scope had the potential to be large enough that it was split up into phases (reference Figure 5.4-1):

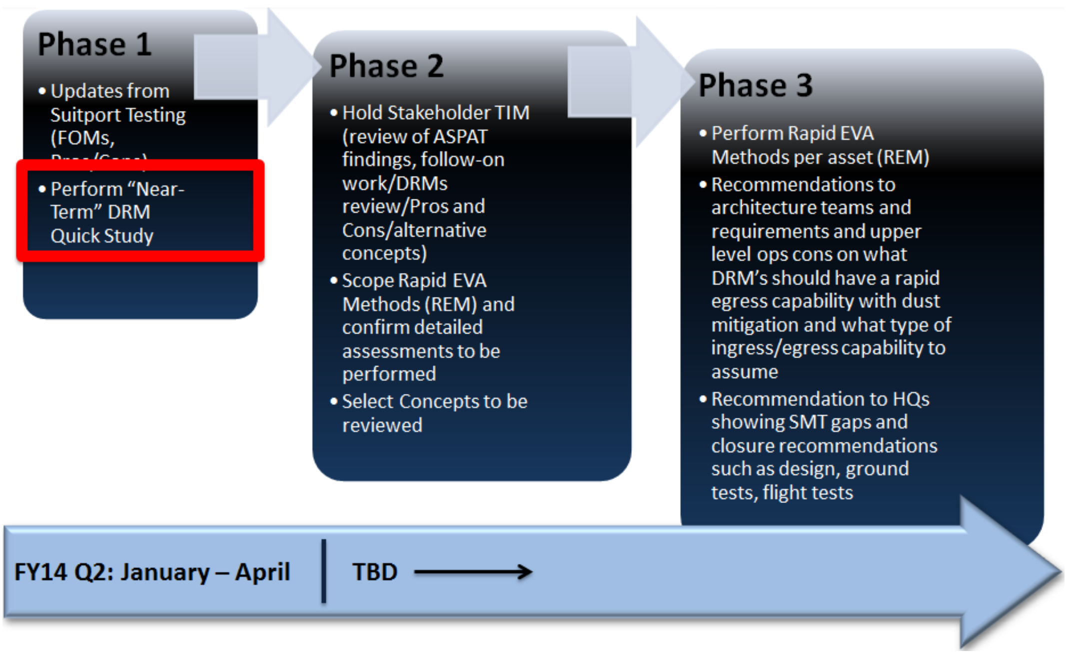


FIGURE 5.4-1 RAPID EVA METHOD PHASES

Part of Phase 1 included the Near Term DRM Quick Study (reference the red box in Figure 5.4-1). It was kept to a very short paper study due to limited resources and funding and was not a study of the same magnitude of ASPAT. The study was specifically to determine if suitports should even be considered in any of the near term DRMs (in the next 20 years) based on a quick look at the Figures of Merit (FOM), especially operational experience, commonality, and extensibility to long term DRMs such as Mars surface. The goal was to provide a non-programmatic recommendation to help buy down risk and document a draft of what can be done in ground testing vs. on-orbit with further work outlined to be done in phases 2 and 3. Phases 2 and 3 were not achieved due to lack of resources.

The scope included a timeframe of 2021-2033 that included the ISS, EAM, Mars Transit Vehicle (MTV), and Mars Moons (Phobos/Deimos). The main ground rules and assumptions included the following:

- Readily available EVA capability with dust mitigation is NOT required for the above DRMs although dust mitigation may very well be required for an asteroid and/or moons of Mars EVA, as clouds of dust may form around an EVA crewmember taking samples

- Suitport is the ingress/egress method when readily available EVA with dust mitigation are required by the DRM
- Suitport needs to be tested on the ground and in microgravity (don/doff, vehicle integration, operational experience for future DRMs in microgravity and Mars 3/8g)
- Suit designed for 8.2 psid
- Exploration Atmospheres (8.2 psi 34% O2) is required for suitport operations and needs to be tested on the ground and in microgravity (DCS can be mitigated, but prebreathe protocol model needs to be validated, need to run exploration atmospheres in microgravity – hypoxia, interstitial fluid and vision impairment); Further information needs to be understood about the combined effects in microgravity, which should be worst case testing

FOMs were discussed and documented as pros/cons due to limited resources. The result of the trade study identified the need to test suitports and exploration atmospheres (8.2 psi/34% O2) on-orbit with the most flexibility being in a suitport-airlock prior to relying on the suitport for mission success on the surface of Mars. After the study, it was discussed that either the rear-entry airlock or depressurizable module could work with the MTV and still be common.

The lunar surface could be the most environmentally representative and ideal place to test; however, it is only discussed in terms of cooperation with International Partners. There are very limited opportunities for testing on-orbit prior to Mars, but it could be done on precursor missions.

Readily available, or high frequency EVAs with dust mitigation are not drivers for ISS, LDRO, or Mars transit EVAs; however, all DRMs could benefit, especially LDRO if exploration of an asteroid is to take place and dust mitigation is required. This is new technology and requires validation testing to ensure mission success in the future. The end-to-end operations of the alternative concept atmosphere in microgravity or partial gravity with an exploration EVA suit will need to be tested to prove the ability to don/doff the suit at a delta pressure, prove vehicle integration as a new system, show that the combined effects on the crewmember are acceptable, and provide operational experience for crewmembers that fly future missions in microgravity and Mars surface 3/8g. While decompression sickness (DCS) can be mitigated, the prebreathe protocol model for exploration atmospheres is different than the ISS prebreathe protocol and needs to be validated. The combined effect of microgravity with hypoxia, interstitial fluid and vision impairment could be tested in microgravity, which could provide an understanding of partial gravity by bounding the problem between 0 g and 1 g effects. Many of the testing considerations discussed during this trade study are in Appendix B.

The following bullets indicate which challenges (as identified in Section 3) have been addressed to some extent in this study:

- Suit Architecture: (in terms of understanding suit interfaces)
- Unassisted Don/Doff: No
- Recharge of all suit consumables (incl. high pressure O2): No
- Volume for donning/doffing and prebreathe: Yes
- Minimal consumables usage with vehicle ingress/egress cycles: Yes
- Increased crew autonomy for airlock operations: No
- Increased quantity and access of EVAs: Yes
- Alternative atmospheres for reduced prebreathe time: Yes
- Volume for in-flight suit maintenance and spares: Yes
- Dust mitigation and Planetary Protection: Yes

The current thinking in the EVA community is that any testing going forward can be completely fulfilled with ground testing and should be tested out to ensure safety for the crewmember prior to flight.

5.5 CONSTELLATION SPACE SUIT SYSTEM (CSSS) SUITPORT ASSESSMENT

A study was performed under the CSSS contract in 2014 to determine the impacts of suitport interfaces imposed on the EVA suit (TDS #1228, D-0588270 05/15/2014) finding significant impacts to cost and schedule. "The many unknowns with respect to environments, operations, exploration assets and external interfaces greatly reduce the ability to adequately assess suit architecture options. Furthermore, many of the functions assumed as being performed by the exploration EVA suit such as Micro Meteoroid Debris (MMD), dust, radiation and thermal protection, stow-mode ventilation and water circulation, and PLSS rotation-translation, could be alleviated by exploration vehicle assets capabilities." The following conclusions were reached that need additional assessment:

- Research and development of hardware and materials necessary to perform suitport-type operations in a planetary environment may significantly increase the overall Design, Development, Test and Evaluation (DDT&E) cost.
- The assessed impacts of a suitport mission on an exploration EVA suit architecture might be mitigated or potentially eliminated by the maturation of a suitport mission design which, at this time, is still very much undefined.
- To design and develop an exploration EVA space suit against an undefined and incomplete requirement set poses cost, mass, and crew

time risks due to the potential re-design necessary to resolve interface, operational challenges and technical risks not yet known.

There are trades from a vehicle perspective that may alleviate the burden on the suit which can help to reduce suit development risk. The following bullets indicate which challenges (as identified in Section 3) have been addressed to some extent in this study:

- Suit Architecture: Yes
- Unassisted Don/Doff: No
- Recharge of all suit consumables (incl. high pressure O2): No
- Volume for donning/doffing and prebreathe: No
- Minimal consumables usage with vehicle ingress/egress cycles: No
- Increased crew autonomy for airlock operations: No
- Increased quantity and access of EVAs: No
- Alternative atmospheres for reduced prebreathe time: No
- Volume for in-flight suit maintenance and spares: No
- Dust mitigation and Planetary Protection: No

5.6 EXPLORATION ATMOSPHERES

Exploration Atmospheres (defined as 8.2 psia / 34% O2) coupled with suitport-type operations is a major paradigm shift from the way operations are done today. Suitport, Suitport-Airlock, and exploration atmospheres are design challenges for the host vehicle. An alternative cabin atmosphere enables readily available EVA by decreasing prebreathe duration (Abercromby, et al., 2015). NASA's Exploration Atmosphere Working Group (EAWG) selected an atmosphere of 8.2 psi and 34% O2 as the best achievable balance of DCS risk, mild hypoxia, and materials flammability (Norcross, J., et al. 2013) after re-examining the 2006 8.0 psia/32% O2 recommendation. The final report from the 8.0 psia/32% O2 working group finding is highly recommended: Recommendations for Exploration Spacecraft Internal Atmospheres: The Final Report of the NASA Exploration Atmospheres Working Group", NASA Technical Report NASA/TP-2010-216134, 2010. The use of a suitport technology system as the method of high frequency or readily available EVAs is dependent on the implementation of the alternate atmosphere; however, the use of an exploration atmosphere is not dependent on the use of suitports. The alternate atmosphere is a driving requirement for systems hardware located inside the pressurized cabin and presents technical challenges to the systems. The EAWG concluded with the following testing needs and recommendations:

- Recommended the Human Exploration and Operations Mission Directorate (HEOMD) formally adopt a development strategy to enable an additional capability for 8.2 psia / 34% O_2 for high frequency EVA phases of missions beyond LEO

- Directed forward work by programs and projects to enable this new capability of 8.2 psia / 34% O_2 in all future exploration Environmental Control and Life Support System (ECLSS)
  - Prebreathe protocol ground test (to validate prebreathe protocols in simulated microgravity & planetary environments & characterize the mild hypoxic environment)
  - Human health & performance at 8.2 psia/34% O_2 with micro-g, elevated Carbon Dioxide (CO_2), Visual Impairment / Intracranial Pressure (VIIP) Syndrome, etc.
  - Materials testing for flammability limits in O_2 rich environments (test to ignition)
  - ISS does not test at oxygen concentrations above 24.1% (30% for the airlock)
  - Orion does not test above 30% O_2 except in special cases associated with avionics bays (where we have obtained threshold data)
  - With a similar philosophy as above, the 34% O_2 environment at 8.2 psia is a nominal oxygen concentration and materials are required to meet flammability requirements at the maximum oxygen concentration – which is 34% plus some quantity based on sensor accuracy uncertainty and control bands (this is expected to be about 1%, so 35% total)
  - Research increased fire risk in reduced gravity environment (early indications that risk is much higher in reduced gravity than micro-g or 1-g)
  - Large-scale microgravity fire tests (Saffire) on three Orbital ATK Cygnus re-supply vehicles scheduled for mid- to late-2016 will evaluate large-scale flame spread and the effect of low-gravity on material flammability limits
  - Additional Saffire experiments being developed to investigate material flammability in exploration atmospheres, fire detection, and post-fire monitoring and cleanup

A memorandum from the HEOMD Associate Administrator for Human Exploration and Operations endorsed the EAWG recommendation that those habitable elements associated with enabling high frequency EVA phases of a mission should be capable of operating at 8.2 psia total pressure and 34 percent oxygen to conduct EVAs, while meeting the Agency's health and safety requirements.

Work on the AES Suitport Project for suitport technology development and associated exploration atmospheres studies were deferred at the end of FY12. An initial assessment by JSC Engineering concluded that the impact to the ECLSS system is likely minimal. Prebreathe protocol ground test (to validate prebreathe protocols in simulated microgravity & planetary environments & characterize the mild hypoxic environment) preliminary testing environments were to be defined and engineering was to develop models for chamber testing. JSC Engineering (EA) was to work with NASA's Human Research Program (HRP) and the JSC Human Health and Performance (HHP) directorate to prepare for appropriate ground testing with an 8.2 psi/34% O2 atmosphere with micro-g, elevated CO2, VIIP Syndrome, etc. However, up to this point, limited additional activities were performed due to shifting priorities and funding availability.

One of the main challenges associated with the combined effects mentioned above is that an 8.2 psia/34% O2 atmosphere has only been approved by HRP for a 1 week duration early in a 30-day mission, but HRP cannot currently certify or approve humans to go to this atmosphere after 30 days. The Mars moons and Mars surface mission concepts include repeated 2 week durations in rovers or surface elements over a 500 day mission. 8.2 psia/34% O2 hypoxia is not a concern for astronauts at 1g, but due to lack of evidence is considered unacceptable today for long duration (> 1 week) exposure in space. No physiological showstopper is anticipated, but forward work is required to validate the new capability. Physiological concerns include vision changes, sleep quality changes, increased fatigue, exercise prescription changes, and sensorimotor and immune dysfunction. The health concern includes the synergistic or additive effects of an 8.2 psia/34% O2 atmosphere and the expected spaceflight environment, including weightlessness, elevated CO2, and radiation (reference Figure 5.6-1).

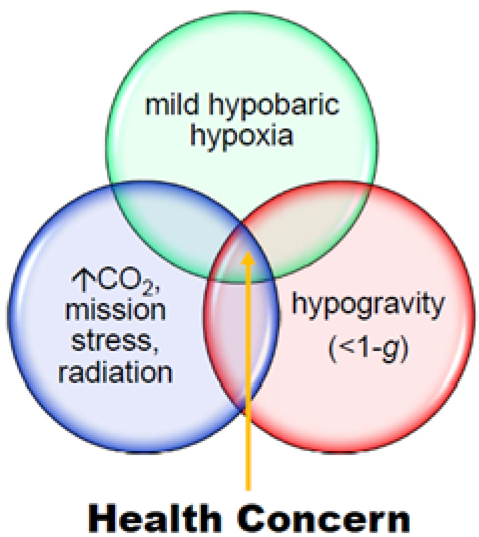


FIGURE 5.6-1 HEALTH CONCERN DIAGRAM

The following bullets indicate which challenges (as identified in Section 3) have been addressed to some extent in this study:

- Suit Architecture: No
- Unassisted Don/Doff: No
- Recharge of all suit consumables (incl. high pressure O2): No
- Volume for donning/doffing and prebreathe: No
- Minimal consumables usage with vehicle ingress/egress cycles: No
- Increased crew autonomy for airlock operations: No
- Increased quantity and access of EVAs: Yes
- Alternative atmospheres for reduced prebreathe time: Yes
- Volume for in-flight suit maintenance and spares: No
- Dust mitigation and Planetary Protection: No

5.7 VERTICAL AND HORIZONTAL HABITATS IN STRATEGIC PLANNING

Different habitat structures have been assessed over the years through projects such as the Deep Space Habitat, Habitat Demonstration Unit analog, and the EAM project. The vertical habitat concept is shown in Figure 5.7-1 (courtesy of Scott Howe),

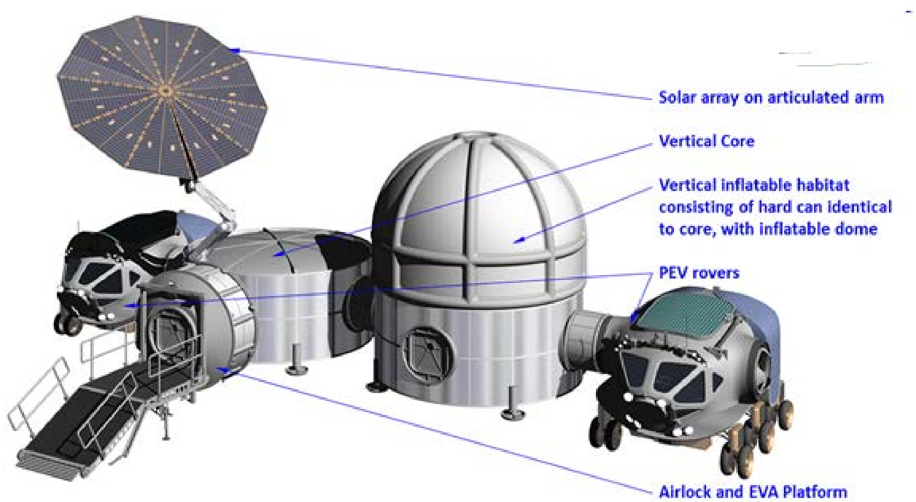


FIGURE 5.7-1 VERTICAL HABITAT CONCEPTS

Cylindrical horizontal habitats have also been studied (reference Figure 5.7-2, courtesy of Scott Howe).

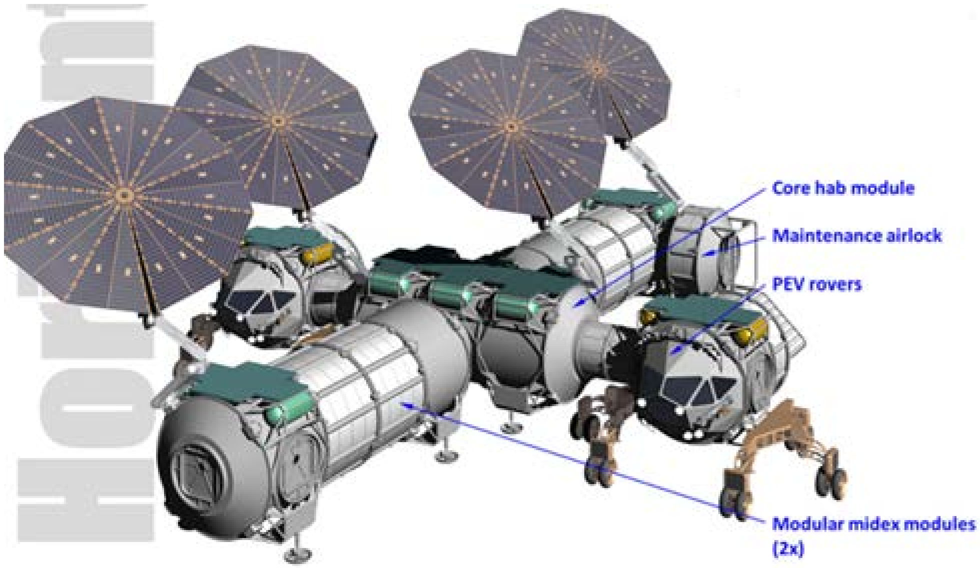


FIGURE 5.7-2 HORIZONTAL HABITAT

Though these structures interface with EVA, habitat orientation is not expected to be a differentiator for EVA as a functional airlock will be needed either way.

5.8 SMALL HABITAT COMMONALITY

A Small Habitat Commonality assessment was performed under the auspices of the Evolvable Mars Campaign (EMC). For this assessment, small habitats were considered to be the Exploration Augmentation Module, the Mars Ascent Vehicle (MAV), a Mars Moon Taxi, a Mars Moon Excursion Vehicle, a logistics module, and a Mars pressurized rover. The following are findings from an EVA perspective in 2015.

While EVAs and suit maintenance will be performed from large habitats on the surface of Mars Moons and Mars surface, there are small habitats that also include EVA capability. In order to look at commonality from an EVA perspective, a high level assessment of EVA hardware and functionality per small habitat was performed to evaluate the number and types of suits in each, hardware, logistics, potential ingress/egress methods, and to gain a better understanding of the masses in each small habitat.

In the current EMC operational concepts, EVA functionality exists on small habitats such as the Mars Moon Exploration Vehicle, the Mars Rover and the Exploration Augmentation Module. EVA operational drivers such as having readily available, high-frequency EVA capability with dust mitigation and shorter prebreathes drive cabin atmosphere to an alternative atmosphere of 8.2 psi, 34% O2 in conjunction with the suitport concept (Boyle et al. 2013). This alternative atmosphere in turn impacts materials selection, suit mass, etc., while potentially saving on vehicle consumables and power. This is beneficial for the Mars Moon Exploration Vehicle and the Mars Rover. For other vehicles, such as the EAM, high-frequency EVAs are not necessary unless used for testing purposes to ensure the alternative atmosphere and suitport operations are vetted prior to use for the first time in the Mars vicinity. Forward work should assess cabin atmosphere commonality and ingress/egress commonality with a large habitat.

Dust mitigation and planetary protection are also factors to consider, which can drive ingress/egress concept design. Dust could also be present near the EAM for potential asteroid missions. While not all small habitats should be common by including EVA functionality, those that do include EVA could all have common methods of ingress/egress. For example, the Mars Moon Exploration Vehicle, Mars Rover, EAM, and the Mars Taxi could all include suitports, suitport-airlocks, or suitlocks (possible commonality with the large habitat); however, past studies have shown that mobile elements (Mars Moon Exploration Vehicle and Mars Rover) should have an unpressurized enclosure (suitports) to cut down on mass and increase excursion range. The quantity of different ingress/egress architectures used across the EMC should be reduced as much as possible. Assuming the baseline for pressurized rovers is the suitport concept, and a large habitat includes the suitport-airlock (which has a pressurizable enclosure and is common with the suitport at a sub-system level), the rest of the ingress/egress methods throughout the campaign could be reduced to two.

Suitports, suitport-airlocks, and suitlocks all include a different hatch size through which the crewmember dons/doffs their suits through a vestibule hatch on a bulkhead. In addition to the suitport vestibule hatch, a larger hatch size (potentially 40” x 40”) must be utilized on any habitat with EVA capability to allow a suited, pressurized crewmember to pass through for EVAs and contingency cases.

EVA Method Options

Discussion/Notes:
- *Ops Con needed
- **Contingencies TBD
- Ingress/egress methods can be common with large habs as well

Suit Options	EAM	Mars Ascent Vehicle (4 crew)	Mars Moon Taxi	Mars Moon Exploration Vehicle	Mars Rover	Could be common with Large Habitat (transit? Surface? Moons?)
Vent cabin	X (traded poorly)	X Cabin Depress or pressurized tunnel to rover*	X (unless conting.)	X (unless contin. maintenance)	√ (If landing in EVA suits, must depress cabin to go EVA to get suits on suitports; conting. Maintenance)	X (unless conting.)
Vent cabin (umbilical)		X (unless conting.)	X (unless conting.)	X (unless conting.)	X (unless conting.)	X (unless conting.)
Suitlock/Rear-Entry Airlock	√ Would be preferred over reg. A/L	X Would be preferred over tunnel	X	X	X	√
Suitport	X	X	√	√	√	X
Suitport-Airlock	√	X Would be preferred over tunnel	√ (systems common w/suitport and rear-entry A/L)	√ (systems common w/suitport and rear-entry A/L)	√ (systems common w/suitport and rear-entry A/L)	√
Airlock (not common with any other DRM beyond ISS)	X	X	X	X	X	X
Airlock (umbilical) (not common with any other DRM)	X	X	X	X	X	X

FIGURE 5.8-1 SMALL HABITAT COMMONALITY EVA METHOD OPTIONS

The other small habitats in this study may include transfer of the EVA suits, but not the functionality to support EVAs. Stowage volume for EVA suits must also be considered during transfer between mission elements. EVA equipment is transferred in the Mars Moon Taxi, MAV, and logistics modules. The Mars Moon Taxi can be common with the MAV, or it can be common with the Mars Moon Exploration Vehicle. The EVA suits must be checked out on-orbit prior to descent. Discussion is taking place on how 4 EVA suits and 4 crewmembers can fit on a Mars Moon Taxi common with a MAV. If the Mars Moon Taxi is common with the Mars Moon Exploration Vehicle, which includes suitports, two suits can be stowed on the suitports during descent to the moons, thus saving volume and potentially addressing this issue. This would also drive the atmosphere to an alternative atmosphere common with the Mars Moon Exploration Vehicles and Mars Rover.

The following bullets indicate which challenges (as identified in Section 3) have been addressed to some extent in this study:

- Suit Architecture: No
- Unassisted Don/Doff: No

- Recharge of all suit consumables (incl. high pressure O2): No
- Volume for donning/doffing and prebreathe: Yes
- Minimal consumables usage with vehicle ingress/egress cycles: No
- Increased crew autonomy for airlock operations: No
- Increased quantity and access of EVAs: Yes
- Alternative atmospheres for reduced prebreathe time: Yes
- Volume for in-flight suit maintenance and spares: Yes
- Dust mitigation and Planetary Protection: Yes

5.9 EXAMPLE INGRESS/EGRESS METHODS

After understanding the challenges and information discussed during past trades (potential impacts to a space suit, benefits for EVA prebreathe, potential impacts due to exploration atmospheres, benefits for pressurized rover traverses, commonality, etc.), the question remains for each new mission element that includes EVA capability – what is the right answer from a vehicle perspective for each new spaceflight project that forms? A preliminary chart from 2014 including ingress/egress methods was examined for a 4 person mission with EVA capability for Asteroid Rendezvous Crewed Mission (ARCM) (shown in the following figure).

- **What Ingress/Egress architecture options do we have today and how might these allow us to improve EVA Availability?**

Airlock Architecture		Internal P Interior Volume	Internal P, Exterior Volume	Dust Mit.	Bulkhead Hatch?	Suit Hatch Seal?	Utilize Exp. Atmos
ISS Airlock (A/L)		10.2+	10.2+ to 0	None	NA	NA	NA
4-crew A/L		10.2+	10.2+ to 0	Min	NA	NA	NA
Next Gen AL	Rear Entry A/L Option	10.2+	10.2+ to 0	Max	Yes	NA	NA
	Hybrid Suitport-Airlock Option	10.2+	10.2+ to 2.0 to 0 (nominally 2.0)	Max	Yes	Yes	NA
	Suitport-Airlock Option	8.2+	8.2+ to 0 (nominally 0)	Max	Yes	Yes	Yes
Suitport		8.2+	0	Max	Yes	Yes	Yes

FIGURE 5.9-1 EXAMPLE INGRESS/EGRESS METHODS

5.10 DEEP SPACE GATEWAY AND TRANSPORT

The EAM evolved to the Future Capabilities Team (FCT) in 2015, which also studied capabilities needed for a cislunar habitat. The FCT formed a relationship under ISS which also included IP involvement. This led to the formal National Advisory Council presentation of phases (shown at the beginning of this document) and included both IPs and commercial partners. This laid the groundwork for the Deep Space Gateway and Transport (DSGT) team established in 2017. In order to prepare for the onramp of NASA studies, including International Partner (IP) integration and evaluation of commercial mockups under Broad Area Announcements, the EVA community agreed upon a set of assumptions to prepare each with a beginning set of EVA assumptions. These will be highlighted in the next section.

6.0 EVA ASSUMPTIONS FOR FUTURE VEHICLES

As new vehicles are developed to meet NASA's exploration goals, interface requirements will be developed between the exploration vehicle and EVA System (space suit, support equipment, tools). These requirements will define values needed to support EVA Operations on and around the vehicle such as worksite envelopes, translation path dimensions, external vehicle touch temperatures, and sharp edges and burrs. While it is expected that program/project specific interface requirements and control documents will be created as each new project arises, the EVA Office has prepared a document in EVA-EXP-0035: Exploration EVA System Compatibility that provides a set of requirements to be tailored to and fed into any new project's interface requirements with EVA. The intent of the guide is to act as a template for developing interface requirements between the EVA system and a program/project and will not be directly referred to or verified to by the program/project. Verifications for the project would flow up through that projects specific Interface Requirement Document (IRD) with the EVA Office. As the guide is based on the EVA Office's prior operational experience it is an ideal source for understanding what the necessary interface requirements between an EVA system and vehicle would be. The following assumptions are given to feasibility study groups prior to the need for an IRD.

The EVA strategic planning community has identified a set of EVA interface needs to provide all future vehicle architecture teams. The assumptions reflect the needs of NASA's exploration EMU (xEMU) but not the design of the ingress/egress method. The needs describe the general utility functions in terms of quality, level, volume, amount, etc. NASA EVA is not specifying the detailed design solution for the Servicing and Performance Checkout Equipment (SPCE) until the PLSS detailed designs are complete, but it is important to derive the supporting vehicle systems utilities "up to the back of the SPCE". As cislunar stack elements and the EVA Systems' flight development plans mature, EVA SPCE will be developed that supports a common approach through cislunar and the follow-on destinations and spacecraft.

- NASA would plan for at least three EVA Suits on orbit to provide the resources and equipment to support US EVA capability for 2 crewmember EVAs. While this does not provide full redundancy for both crewmembers, it is an assumption to carry some redundancy until component R&Rs are better understood. This is also assuming no other commercial or IP suits on orbit, in which case it could be argued these other suits provide the redundancy needed reducing the number of US suits to two.

- EVA logistics/ancillary needs are based upon the number of EVAs per mission.

- NASA would provide any SPCE needed to go between the general airlock utility services and the exact, specific output needed by the NASA EVA suit. This enables maximum flexibility for the airlock developer while also allowing for the independent definition and detailed development of the US EVA SPCE hardware.

- Umbilical Interface Panels for International Partner-provided and NASA-provided EVA suits could be separate or combined. This allows each EVA Suit provider to manage and develop their detailed suit interfaces without over-complicating the design of each country's SPCE hardware. A downside of separate UIPs allows for the potential of multiple different versions, which would be a significant problem when looking at stowage in any spacecraft.

- EVA translation assumes the use of double safety tethers vs. Simplified Aid for EVA Rescue (SAFER) pending a discussion with NASA Safety on fault tolerance for cislunar and Mars transit.

- For an EVA crewmember to safely translate through a hatch in microgravity, the hatch must be sized such that the largest suited, pressurized crewmember will be able to fit through. The airlock would include primary and secondary hatches large enough (1000 mm.) to allow a pressurized suited crewmember to exit and enter the vehicle.

- Unpressurized EVA components can be transferred through an NASA Docking System (NDS) hatch (31.5 in.).

6.1 EVA CONTINGENCY SECONDARY INGRESS HATCH AND DUAL CHAMBER AIRLOCKS

While not all vehicle or ingress/egress designs require both a primary and a secondary EVA hatch, an analysis of failure modes could reveal the need when coupled with program-specific choices for human rating and redundancy/fault tolerance strategies. Fault tolerance should be included in the detailed mechanism designs; however, there are some failure modes that may not be able to be mitigated without adding a secondary hatch. Fundamental failures can be <u>grouped</u> into the following categories:

- Failure of Extravehicular (EV) Hatch to close
    - o This could include binding/jamming of hinges, loss of alignment of hatch mating halves, or failure of locking mechanism (design details TBD)
- Failure to equalize airlock pressure with the vehicle

  - This could include external leakage through EV hatch/seals or failure of the equalization system that pressurizes the airlock

There are three conceptual options for conventional airlock volumes (this does not include the suitport concept):

- A stack with a “Single Chamber” airlock element
  - This is operationally similar to “Capsule Based EVA” such as the ARCM baseline, though the size might allow for nominal Exploration EVA Suits
- A stack with a “Dual Chamber, Conjoined” airlock element
  - This is operationally similar to the Joint Airlock on ISS, providing a separate crew and EVA equipment lock which can each function as an airlock in the event of a hatch or repress failure
- A stack with a “Dual Chamber, Separately Located” airlock element
  - Airlock and Orion (this incurs other risks such as isolating the Intravehicular (IV) crew, Orion preparation, volume, translation paths, and umbilical transition interfaces; Orion may not travel with Mars transit habitat)
  - Note that a full EVA suit cannot currently make it through the Orion side hatch without modifications to both hatch mechanisms, IVA translation aids, and the EVA system
  - Airlock and Habitat element (this incurs other implications such as equipment designed to go to vacuum, umbilical interfaces, preparation, external hatch access, etc.)

It is important to note that Orion can be used as an airlock to support EVA capability. Therefore, it would be possible to depend upon the docked presence of Orion for any contingency EVA needs. There are, however, a couple of safety-related, risk considerations with this approach. First, when Orion is docked to the spacecraft, it represents the life raft in the case of the need to escape the spacecraft in an emergency. If Orion is depressurized in order to support an EVA, then it is not immediately available to function as a life raft. In this state, several time-consuming steps would be required before Orion could be returned to a state sufficient to support evacuation of the cislunar, proving-ground spacecraft. Thus, using Orion as the contingency airlock represents a high-risk choice. Second, there may be planned periods where a crew will be present on the spacecraft and Orion will not be docked. These would be intentionally high-risk missions endeavoring to eventually evolve to Mars mission capabilities where abort possibilities will be limited or even nonexistent. In this situation, already high risk with Orion not present as the life raft, it is likely not appropriate to also be entirely without the capability for contingency EVAs. Thus, based upon these considerations, the requirement for the inclusion of contingency EVA capability on a cislunar stack is clarified further to state that it must be independent of this capability existing on Orion. This kit-based approach is further documented in EVA-EXP-0042 Exploration EVA System Concept of Operations.

The EVA community assumes that a cislunar stack and surface habitats will include secondary ingress capability at the very least. A dual chamber airlock (equipment lock and crew lock) provides secondary ingress capability as well as the sufficient access and free volume necessary to perform all of the aforementioned activities to conduct EVAs. The crew lock can then be optimized for minimal consumables depletion.

6.2 EVA INTERFACES

General interfaces between an exploration EVA suit and exploration vehicle are outlined in Figure 6.2-1. A future ingress/egress method would incorporate interfaces associated with a new EVA suit, including consumables recharge such as high pressure O2, water, and power. Other utility style interfaces not conventionally used thus far in EVA may also be needed such as high throughput vacuum interfaces. General EVA interfaces between the vehicle and the EVA SPCE are summarized in the graphic below. This is used as a checklist for the summary of current NASA xEMU EVA to Airlock interface details.

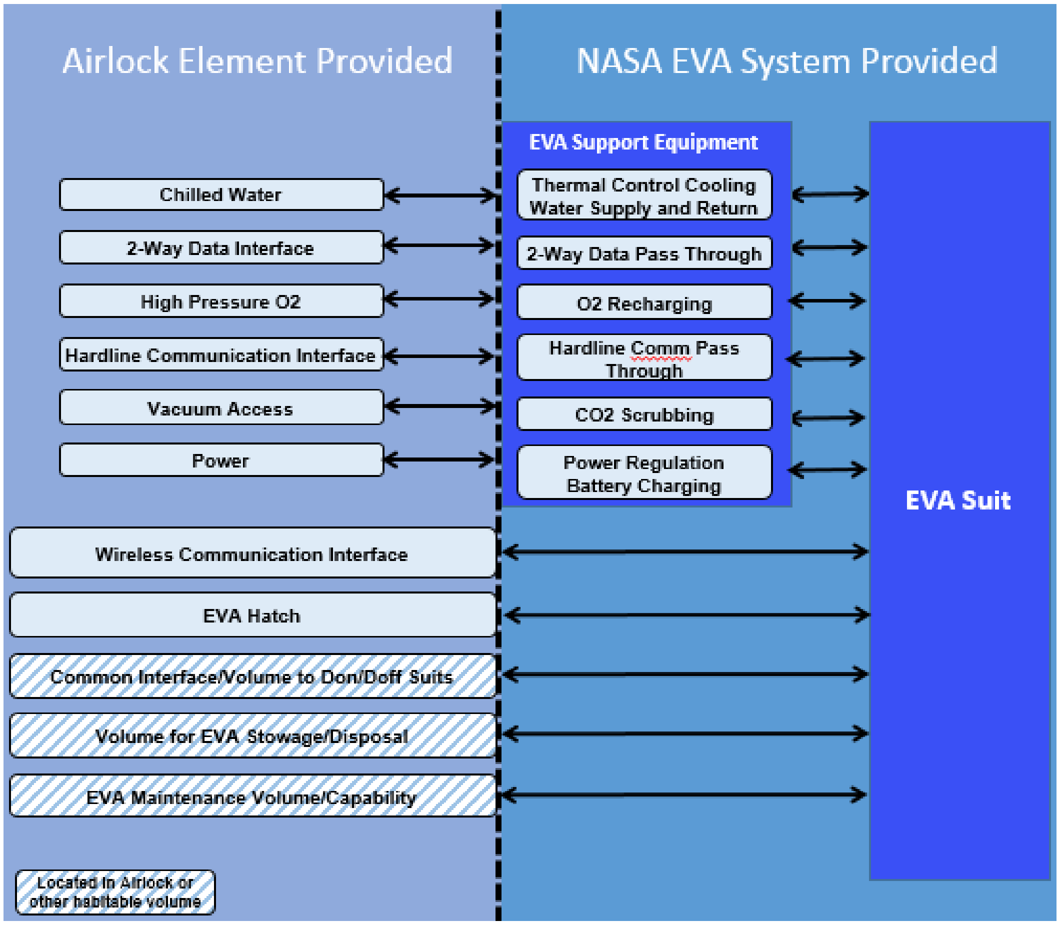


FIGURE 6.2-1 GENERIC EVA INTERFACES DIAGRAM

6.2.1 EVA Interface Details

- Power
  - Umbilical Power (hardline during IV Suited Ops)
- Average power draw during EVA prep: 400 W; Peak 900 W
  - Battery Charger Power (EVA prep/post servicing)
- 40 W idling; Peak 110 W
- Oxygen: For the purposes of this assessment, EVA O2 Demand is defined as any event that causes the EVA System to draw upon oxygen resources stored directly in a tank or through the transfer medium of the cabin atmosphere. The following line items are representative events that cause EVA O2 Demand:
  - Suit Maintenance (such as EMU Airlock Cooling Loop Recovery Unit (ALCLR) Loop Scrub on ISS)
  - On-Orbit Fit Verification (OFV)
- OFV's only occur 1+ per crew for their time on orbit, NOT every EVA a given crew member conducts

- The number of occurrences change per DRM (long duration, partial gravity, etc.)
  - Prebreathe Protocol gas loss (changes per DRM)
  - Cabin Atmosphere for Airlock repress (whatever is not reclaimed)
- Residual air after airlock depress (gas loss vented after air reclamation)
  - EVA Consumables *lost during the EVA itself*
- xEMU Suit Leakage and Met Rate
- High Pressure O2 Recharge (EVA prep/post servicing)
  - 3000 psia O2 @ 99.5% O2 (MIL-PRF-27210G Type I, 99.5% O2 with balance of N2/Argon + allowable contaminants in Table I of the mil-spec); a purity range may be moved from EVA-RD-001 Exploration EVA Suit Systems Requirements Document (now SSP 51073) to this document in a future update
  - Cleanliness 200A
  - Total O2 needed for 10 EVAs:
- 140 lbm (prebreathe, fit verification, recharge)
- Water
  - For the purposes of architecture evaluation and consumables estimates EVA assumes beyond LEO Exploration EVA Systems use water as a utility consumable for cooling of the EVA Crewmember during the EVA (drinking water assumed to be included in everyday IVA water consumption)
- JSC-66695 EMU Water Quality Spec as reference
- Cooling water recharge volume of 1 lbm water/hour per EVA crewmember (160 lbm per mission assuming 10 EVAs)
  - Biocide
- A trade is ongoing on preferred Biocide – Either Silver nitrate 0.3-1ppm in the feedwater supply or Iodine 0.5-6 ppm; Whichever is selected, a goal is to achieve a common Biocide
  - Cooling Water (hardline during IV suited ops prep/post servicing)
- The temperature of the cooling water received from the Airlock for return to each xEMU will not be greater than eighty-eight (88) degrees Fahrenheit at a flow rate of 187 lbm/hr
- The temperature of the cooling water received from each Suit is not greater than ninety-eight (98) degrees Fahrenheit at a flow rate of 187 lbm/hr
  - Waste Water (EVA prep/post servicing)
- Many options are acceptable, including waste water drain to either a consumable bag or a vehicle receptacle. The rate needed is a maximum of 30 lbm per hour against a back pressure of up to 8 psig per suit

For the purposes of feasibility studies, consumables for 10 two crewmember EVAs were computed based on both EMU calculations and xEMU estimates in Figure 6.3-1:

Consumables per EVA Crewmember per EVA	
High Pressure (3000 psi), High Purity O2	1.7*2 crewmembers*10 EVAs=34 lbm
Low Pressure, High Purity O2	5.13*2*10=102.6 lbm
Low Pressure, Air	? lbm (cabin depresses per vehicle)
Water	8*2*10=160 lbm
Power	TBD
Consumables per EVA Crewmember per Suit Maintenance and OFV	
High Pressure (3000 psi), High Purity O2	0 lbm (1/month)
Low Pressure, High Purity O2	0.15 (1 On-orbit Fit Verification/mission per crewmember)*2 crewmembers = 0.3 lbm
Low Pressure, Air	?
Total Consumables per mission (10 two crewmember EVAs, two OFVs)	
High Purity O2	136.9 lbm or ~140 lbm
Water	160 lbm

FIGURE 6.3-2 GENERIC EVA INTERFACES DIAGRAM

- Vacuum Access (support for CO2 Removal and Regeneration during IV Suited Ops)
  - Vacuum source capable of providing a vacuum of <0.1 torr
- Volumetric flow rate >1150 lpm (single flow rate addressing two suits) at 1.6 torr
  - Vacuum source capable of tolerating O2, CO2, H2O, and NH3
- Qmet = 400 BTU/hr (metabolic rate for each crew member)
  - CO2 = 37 g/hr per suit => 74 g/hr total
  - H2O = 44.3 g/hr per suit => 84 g/hr total
  - Used for ~3 hours prior to EVA, 1 hour post (supports suited IV operations including EVA Prebreathe and post-EVA doffing)
- Communication Interfaces: EVA Assumes all stack elements are outfitted with infrastructure/utility that will support deployment of both IVA and EVA nodes for wireless and hardline communications. The vehicle will provide active radiation monitoring and an alerting function to signal the suit to alert the crewmember via high reliability transmission. The current exposure limits for deterministic effects (short-term exposure limits) are

specified in NASA-STD-3001, Volume 1, and to demonstrate compliance, radiation monitoring is required. Reference NASA-STD-3001, V2 requirement V2 11010.

– Wireless Communication Interface

- High reliability UHF
- High rate 802.11

– Hardline Data and Communication

- 2-Way Data Interface
- Hardline Communication Interface
- Consumables implications would need further discussion (air reclamation/airsave)

6.2.2 EVA Volumes

Volumes needed for EVA capability include volume for EVA stowage, volume to don/doff EVA suits (including prep/post servicing), volume for suit maintenance, volume for NASA-provided EVA SPCE, logistics, common vehicle tools and science tools, volume to egress/ingress the vehicle, and volume for large ORUs/equipment (if applicable) that need to be transferred via EVA from IVA stowage to outside of the vehicle.

Volume for EVA stowage would include enough volume to stow three exploration EVA suits (cislunar) to four EVA surface suits plus any spares needed for the mission. The stowed volume for three EVA suits would be on the average of 1.75 m^3. Some of this volume can be combined with the volume the crew uses to don/doff the suits and perform maintenance. Trade-offs would be available to stow EVA hardware in locations other than the airlock, such as a logistics module; however, this would be a crew time/efficiency consideration.

While thinking of minimizing volume to depress in order to conserve consumables, the volume cannot be limited too much, such that the prevention of entrapment and/or suit damage is not a concern. Mockups and testing should include all equipment needed in the airlock.

The EVA community assumes the capability for two crewmembers to self don/doff suits simultaneously with the ability to view each other. It is assumed the equipment lock portion of a dual chamber airlock would be used similar to ISS procedures. Currently on the ISS, a third IV crewmember assists the EV crewmembers during don/doff procedures. A minimum volume of 7 m^3 is assumed to be necessary for simultaneous donning (this does not include a third IV crewmember). Further analysis is necessary to determine volumes. Serial donning could be considered for smaller airlock designs; however, this would be a hit to the crew timeline and efficiency on an already packed EVA day.

Volume necessary for NASA-provided EVA SPCE, minimum logistics, common vehicle and the minimum necessary microgravity tools could be on the order of 1 m^3. Extra volume may be needed for equipment to support both RS and US operations.

EVA tasks must be considered during airlock concept design in order to understand whether or not large ORUs or payload volumes will need to be accommodated for with two crewmembers in the crew lock. Heritage programs have to prioritize critical tasks due to the size of the ORUs/payloads.

For surface operations, volume would be needed for suit maintenance, as the luxury of sending suits back to Earth for refurbishment/certification gets less feasible the farther out humans explore. Additionally, for the design reference missions that include suitports, suits must be brought inside a habitable volume for most, if not all, maintenance tasks.

6.3 EVA NEEDS FOR TRANSLATION PATHS (μg)

Further refinement of cislunar stack concepts with commercial or international partners will lead to EVA translation path definition. Task definition, stack design layout, and robotic interface locations and reach envelopes are necessary to define translation paths along the elements of the stack. Translation paths are required on the airlock and should lead to the paths based on the tasks.

Task Definition includes:

- External vehicle maintenance: PDR-level vehicle design concepts should reveal if there are any stack failures EVA may be used to mitigate
- External payload installation, removal or interaction: Architecture maturation should identify if there are any needs for EVA interaction with payloads
- Interaction with other spacecraft or docked objects: Mission scenarios will determine which docking interfaces EVA should be able to translate to/across
- Other contingency scenarios: Cislunar stack utilization/mission assurance analysis will determine if there are any other contingencies which require EVA for mitigation (examples may include failure of returning excursion vehicles to dock/seal)

Stack design layout:

- Some items may not be designed to withstand EVA induced loads because of their function and/or mission limitations. Translation paths will need to be located to avoid those areas. Further definition of these items and their placement will help determine remaining locations for handrails and translation paths. Keeping track of what meets kick loads (or other limit loads) is practically a full time job on ISS. Many of these become "no touch" i.e. no kick or load sensitive and crew must be either trained or told by ground crew to manage each case. Since my understanding of future missions is delayed com/more autonomous crew, anything you do to make special cases that the crew has to be warned about or remember creates a potential hazard

- Other external hardware which may pose hazards to EVA crew (such as sensitive instruments, comm antennas, moving solar arrays, ejection paths, etc.) may be categorized as keep-out zones which will also influence the placement of the EVA translation path hardware

Robotic interface locations and reach envelopes:

- How far robotics can reach, grapple, and interact with EVA Crew could alter EVA translation path design.

7.0 FUTURE TRADES FOR VEHICLES

Moving forward, the EVA strategic planning community has recognized the need to document the main trades and past discussions involved with ingress/egress methods as a primer for new vehicle concept teams trading EVA architectures. Some of these trades are very abstract and are not focused on any one vehicle architecture, but rather on common features such as hatches. Though abstract, these trades are listed here because they consistently emerge in all human spaceflight programs and studies under development such as ISS, CxP, and the HAT EMC strategic planning. While these trades are common across all of these programs and projects, there is not yet a communally agreeable solution because the FOMs change as the mission objectives change. Though there is not as yet a one-size-fits-all solution, it is thought that proactive studies can however trade options with the expectation of identifying families of vehicle architectures and corresponding families of ingress/egress solutions. Most of the future trades described in this section have direct influence on an exploration EVA suit or operations and may need to be very detailed.

This section is organized in tiers based upon the scope of potential trades. The section begins with a very broad overall mission section, followed by habitable volume and associated ingress/egress method trades, and trades involving suit versus vehicle functions.

7.1 OVERALL MISSION

The overall mission architecture will determine the FOMs by which each ingress/egress method is evaluated. While mission architecture design and campaign assessment are beyond the scope of this document, the merits and findings of individual concepts and trades can dramatically change when evaluated for different mission architectures. Thus, each detailed trade should consider the weighting of FOMs and how that would change across various DRMs. Such variable sensitivity should be included in future trades as a way of validating the findings. A general listing of the concerns and perspectives is included in the following subsections; for further understanding of the spectrum of trades under consideration for beyond LEO human exploration, please see the Global Exploration Roadmap (GER, International Space Exploration Coordination Group (ISECG), 2013).

7.1.1 Overall Mission Asset Trades

Currently, missions being developed and evaluated are intended to be evolvable campaigns and kept at a high enough level that certain assumptions may be interchangeable/adaptable to future policy directions.

Listed here are the fundamental questions that must be considered and addressed as any DRM is created. More than any other detailed trade, the answers to these questions will have greater influence on the EVA capability a given space flight architecture possesses:

- What are the overall mission objectives?
- Is it assumed that EVA capability is contingency only, or are there nominal EVA tasks planned?
- If there are contingency EVA tasks planned, what is their nature?
    - Are there certain known failures that require an EVA crewmember to fix such as a failed ORU changeout?
    - Does the architecture desire to attain any capability to address unknown or unplanned failure modes?
    - Is a simple "fail to dock/hard seal" scenario requiring a hatch to hatch transfer a valid risk?
- If there are nominal EVA tasks planned, what is their nature?
    - Are there external experiments on the vehicle that may need an EVA crewmember to install/enable/fix?
    - Are there assembly or maintenance tasks?
- How far from a habitat is the EVA crewmember capable of going for exploration and research?
- How often will EVAs be performed?
- How many EVAs will be performed?
- How long will each EVA be in duration?
- How long is the mission?
- How long is uncrewed portion of mission (quiescent mode)?
- What mass and volume is available for the entire EVA system, including the ingress/egress method?
- What is the testing lead time for suit compatibility, partial g delta pressure don/doff and human research clinical trials to address any unknown physiological risks by the 2030s?
- What are possible mitigations in lieu of this?
- Is dust mitigation required?
- Is planetary protection required?

The architectures chosen will affect testing and each phase of the mission through launch, transit, landing/rendezvous, emplacement, daily operations, ascent/departure and crew return.

Once the EVA capability is determined, the following challenges should be considered when determining ingress/egress methods:

- Suit Architecture
- Unassisted Don/Doff

- Recharge of all suit consumables (incl. high pressure O2)
- Volume for in-flight suit maintenance and spares
- Volume for donning/doffing and prebreathe
- Minimal consumables usage with vehicle ingress/egress cycles
- Increased crew autonomy for airlock operations
- Increased quantity and access of EVAs
- Alternative atmospheres for reduced prebreathe time
- Dust mitigation and Planetary Protection

These challenges are embedded in most, if not all of the trades listed below and the reader will recognize the list from the status summaries of previous/historic trades. Listing out the vehicle mission purpose first is important to closing an entire mission and campaign level operational concept. For instance, a mission with contingency-only EVAs should still address each of the challenges above to determine the method of ingress/egress, even though an exploration class mission may address them to a greater extent or in different ways.

7.2 HABITAT AND INGRESS/EGRESS METHOD TRADES

A study of past airlocks and vehicles can show different perspectives on what they were used for, what worked well, and what should be considered going forward. See Appendix D for details. The following sections highlight a series of trades for habitats and ingress/egress methods.

7.2.1 Ingress/Egress Method: Integral to vehicle or separate module?

Whether or not the ingress/egress method chosen for the vehicle is integral to the vehicle or is a separate module has been a topic for discussion throughout human spaceflight. An ingress/egress method in which the full bulkhead is being used as the pressure bearing end is considered integrated. Most legacy airlock hardware has either been as a separate module, like the ISS Joint A/L or an entire cabin depress using the cabin itself as the airlock like Gemini and Apollo (Figure 7.2.1-1).

Past and Current Airlock Architecture	Integrated or Separate
Gemini Capsule	Integrated
Apollo Lunar Module	Integrated
Skylab	Both (Internal)
MIR Voskhod (Inflatable)	Separate
MIR	Separate

ISS Russian A/L: Pirs Docking Module 1	Separate (Dual use as A/L and docking port)
ISS Russian A/L: Poisk Mini-Research Module 2	Separate (Dual use as A/L and docking port)
ISS Russian A/L: Zvezda Service Module Transfer	Integrated
Shuttle A/L	Separate
ISS Joint Quest A/L	Separate

FIGURE 7.2.1-1 INTEGRATED VS. SEPARATE AIRLOCK FUNCTIONS

When discussing the use of suitports on a small pressurized rover, the suitports are often depicted as integral to the vehicle itself (reference Figure 7.2.1-2).

FIGURE 7.2.1-2 SUITPORTS INTEGRATED WITH PRESSURIZED ROVER

The rear-entry airlock and suitport-airlock have also been shown to be integral to horizontal habitats (reference Figure 7.2.1-3) or can be shown as a separate module (reference Figure 7.2.1-4):

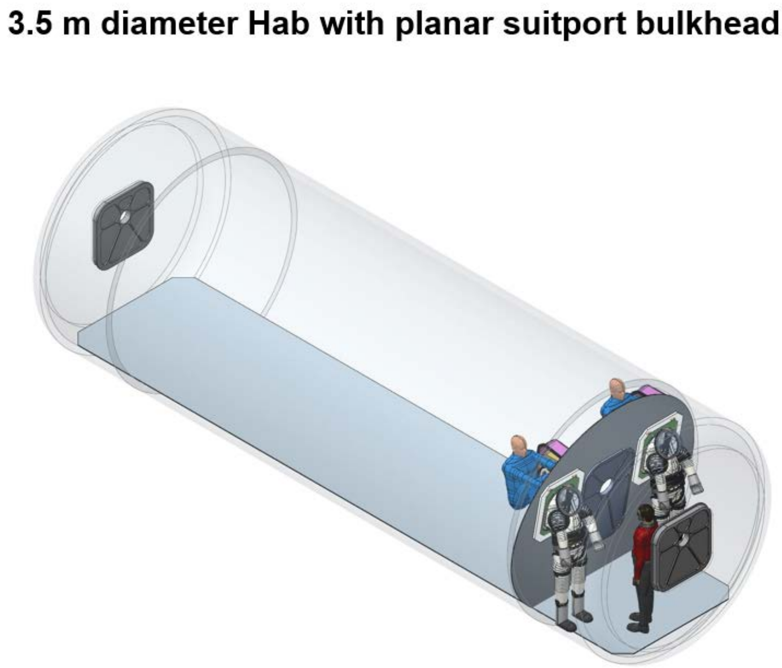


FIGURE 7.2.1-3 INTEGRATED HORIZONTAL HABITAT CONCEPTS

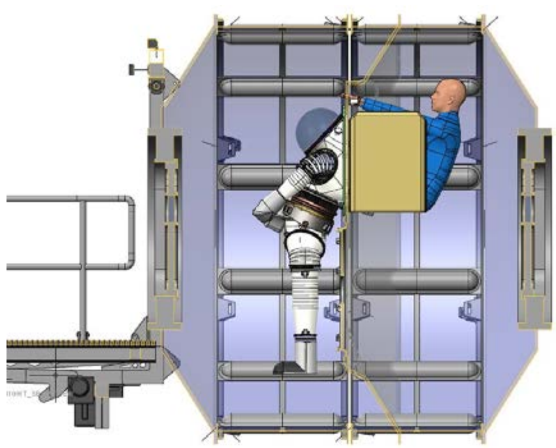


FIGURE 7.2.1-4 SEPARATE MODULE FOR REAR-ENTRY AIRLOCK OR SUITPORT-AIRLOCK

Ingress/egress methods for habitats and other vehicles, such as test vehicles, transit vehicles, landers, and ascent vehicles are less certain with the possibility of either an integral ingress/egress method or a separate (add-on) ingress/egress method which includes additional volume (reference Figure 7.2.1-5).

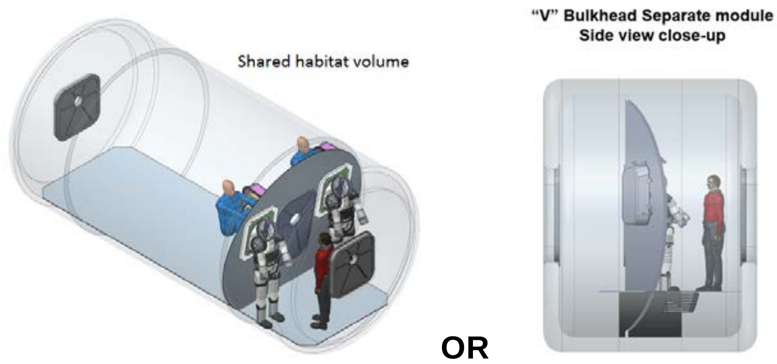


FIGURE 7.2.1-5 INTEGRATED OR SEPARATE INGRESS/EGRESS CONCEPTS

Having the structure with additional volume as an "add-on" has pros and cons that need to be considered and weighed. The following sections include further detail on both the add-on concept and the integrated concept.

7.2.1.1 Ingress/Egress Method as a Separate Add-on Module

An add-on module could allow some amount of flexibility in the development and delivery schedule depending on when/where the module is to be flown. If considering near-term, and the estimated launch date of a vehicle precedes the completion date of the ingress/egress method being developed, it could be delivered separately at a later date when flight ready. For example, this would not be an issue for an ingress/egress method development project going to the ISS due to the already present EVA capability from both the Russian segment and the United States segment. If discussing a different vehicle at a location other than ISS, the capability to go EVA may not be available until the arrival of the "add-on" ingress/egress method, so the risk level would need to be discussed or the vehicle could be depressed for contingency EVA use until the add-on arrives (assuming it is designed and constructed to be EVA compatible). This could pose additional concerns, such as consumables for an entire cabin depress/repress, and the certification of all items in the cabin to sustain capability after exposure to vacuum. Many vehicles have found this to be an undesirable trade.

As long as the host exploration vehicle and the add-on module fit within the shroud of the launch vehicle and the schedule allows (the ingress/egress method development is completed in parallel with the host vehicle) they could be launched connected. Depending on the launch vehicle used, an add-on module could mean an additional launch if the stack does not fit or if not launched attached to the vehicle. Volume inside the Space Launch System (SLS) or other launch vehicles would need to be analyzed. If the add-on module fits with the host vehicle inside the launch vehicle shroud, it would most likely still be more mass than an integrated concept.

Depending on the design and layout of the vehicle, an add-on module could be berthed to other ports of the vehicle as opposed to being attached to the end of the vehicle (some vehicle concepts show propulsion modules or other vehicles on the ends). This decreases the chances that the add-on module could be flown with the host vehicle inside the launch vehicle shroud, which could lead to on-orbit installation.

Installation of the add-on module should also be considered. Attachment could be performed with robotics, but depending on the complexity of the attachment mechanism, it may take EVA to install, so the vehicle/module that it is attached to would have to go to vacuum for installation, unless it has an additional airlock. For surface ops, an offloading technology (presumed necessary for surface ops) could be used to connect the add-on module to the habitat. One choice to make is whether or not the habitat remains on the lander or is offloaded to the surface. If the habitat is left on the lander, discussion needs to take place on how the astronaut translates up and down from the surface to the ingress/egress method via stairs, ramps, etc.

An add-on module could potentially be common and used with any vehicle design concept (microgravity vehicle or surface horizontal or vertical habitats) depending on pressurizable volume, maintenance capability, and atmosphere. It also has the ability to be relocated or replaced.

An add-on module (assuming it is not a single volume or regular airlock) could provide enough volume to perform a prebreathe if such is necessary at a pressure different than the primary stack. Otherwise, the host vehicle or habitat would need to provide prebreathe capability at the EVA prebreathe or the crewmembers would have to endure significant prebreathe time using mask protocols. For example, this would be the case for a large habitat with a small Shuttle-sized airlock. In this case, the airlock volume is too small to don the suits and prebreathe, which places the burden of the prebreathe atmosphere on the habitat. See Figure 6.2.2-1 for further habitat atmosphere trades.

7.2.1.2 Ingress/Egress Method Integrated with the Host Vehicle

Clearly, an integrated ingress/egress method with the host exploration vehicle would be schedule dependent on one another’s development. If the ingress/egress method design is to be integrated with the vehicle and the design of the method is delayed beyond the estimated delivery date of the vehicle, the schedule would have to be adjusted.

Having the structure integrated with the host vehicle is a permanent solution and would be launched with it (no EVAs for installation, no extra launch).

If used, an alternative atmosphere of 8.2 psia/34% O2 or similar prebreathe atmosphere would be created in the host vehicle cabin with a suitport or suitport-airlock concept as there is not a separate chamber in which to perform a long prebreathe.

On a vehicle/module that is not docked at ISS and/or is standalone and includes the suitport concept, everything inside of at least one compartment must be vacuum compatible to allow for contingency entrance through a side hatch for contingency suit maintenance. This is not true for the rear-entry airlock or the suitport-airlock since the volume around the suits can be pressurized and an internal hatch is included in these concepts.

As opposed to an add-on module, an integrated structure inside of a horizontal habitat on the forward or aft ends of the cylinder (horizontal habitat for microgravity or surface) would be a much lower mass since it is utilizing an end cone bulkhead instead of adding on a completely separate module. The additional mass on an integrated structure would mainly be the internal bulkhead with the suitport/suit access hatches and an internal hatch (for rear-entry airlock and suitport-airlock). The mass of the outer end cone bulkhead is therefore shared between habitat and ingress/egress method.

7.2.2 Logistics Module Conversion to Airlock

In order to save upmass, a discussion on converting a logistics module to an airlock became a topic of discussion. Any airlock would need to be designed and constructed to be EVA compatible and would need to include EVA interfaces and assumptions listed in section 6 of this document. A quick look resulted in the following:

- What is the trade of cost of using the logistics carrier, cutting the primary structure, and outfitting with ECLSS/Thermal/hard mounted equipment vs. building an airlock element?
- Primary Structure changed for EVA hatch size TBD (2 axial)
- EVA Servicing Equipment Kit based vs Hard mounted: Hard mounted
  - Assume hard mounted due to criticality of dust mitigation, planetary protection, etc. (assume ground tested)
  - ECLSS and Thermal should be plumbed (would want to get their input) – has its own depress/repress pump and active coolant loop
  - Include consumables tanks pre-connected: high pressure O2 lines and water lines, etc.
  - Using In-Situ Resource Utilization (ISRU)? Include refill connections
  - Secondary structure included for panels and plumbing

- Question of how you would transfer O2, water, air, comm, data, etc. through the tunnel concept (connects directly to the modular habs)
- Assume it includes:
  - Suit/general maintenance area
  - Dust mitigation
  - Secondary ingress capability (could use rover cabins as secondary ingress acceptable – operationally would have to be available)
- Dust Mitigation/Planetary Protection
  - Dual chamber with internal bulkhead
- Hard bulkhead with Single hatch (don/doff stands in crew lock for layered engineering defense) vs suitlock (rear-entry airlock)
- External inflatable crew lock

It was not discussed whether the logistics module is converted on orbit (i.e., repurposed after delivering cargo) or if it would be a module outfitted on the ground and flown as an airlock. Repurposing a used logistics module on orbit could be more upmass-intensive than simply building a dedicated airlock on the ground. It could be that modifying one on the ground would be about as expensive as building from scratch. Building from scratch also would avoid many design compromises that would have to be considered when trying to convert a module to a purpose for which it was never designed.

However, the ISS RS airlocks use modular suit supply hardware that could be integrated into an existing module.

7.2.3 Host Vehicle Atmosphere

The dual chamber airlock, rear-entry airlock, suitport, and suitport-airlock concepts are dependent upon the vehicle's ECLSS alternative atmosphere settings. An integrated ingress/egress method would rely on the vehicle's ECLSS, therefore playing a role in how an EVA prebreathe protocol is determined. There are many variables that are included in determining an EVA prebreathe, including the duration the crewmembers are at a certain atmosphere/O2 level, gravity level, etc.

An add-on module could be built to include alternative atmospheres allowing the host vehicle to avoid the alternative atmosphere by isolating the two with a hatch. The add-on module may have to include a minimal galley and waste control management (which adds mass) such that the crew can camp out for longer periods of time in order to adjust to the alternative atmosphere for prebreathe prior to going EVA. During the Near Term DRM Quick Study, it was found that having a separate module without a minimal galley and waste control management was unacceptable as the crewmembers would have to stay in Maximum Absorbent Garments (MAG) and take food and water into the chamber with them for an extended amount of time to adjust to the alternative atmosphere. The host vehicle will have to be compatible with the alternative atmosphere if the add-on module is not large enough to include a galley and waste management system.

There are quite a few trades to look at when considering bringing down a vehicle from a sea level atmosphere to any other atmosphere designed to decrease DCS risk and EVA prep time. Whether the air from the habitat or vehicle stack is vented, reclaimed into another part of the habitat, or pumped into other gas tanks could determine differences in overall mass and consumables necessary. The point at which the mass of the consumables/tanks equals the mass of an integrated or add-on module should be considered to help inform architecture decisions. ISRU also has an influence on consumables and should be considered, but it is still a low Technology Readiness Level (TRL) technology in the context of relying upon it to provide high pressure and high purity O2 for use in EVA applications. EVA suit impacts have already been brought up in this document, but medical concerns should be understood further. Assuming that mission designers are trading stack architectures or have already chosen a vehicle ingress/egress method, one still has to trade the habitat saturation pressure the crew will live at long term or live at short term prior to determining a prebreathe protocol and the corresponding prebreathe duration that is acceptable for the frequency of EVA envisioned. Although it is significantly advantageous for EVA to utilize crewmembers saturated at ever lower habitat operating pressures because of the corresponding reduction in prebreathe time, as discovered in the previous Exploration Atmospheres trade (see Section 5.6 and Figure 7.2.3-1) many vehicle systems have not been conventionally designed to operate at such lower pressures and conversion of them to do so creates the appearance of delta cost.

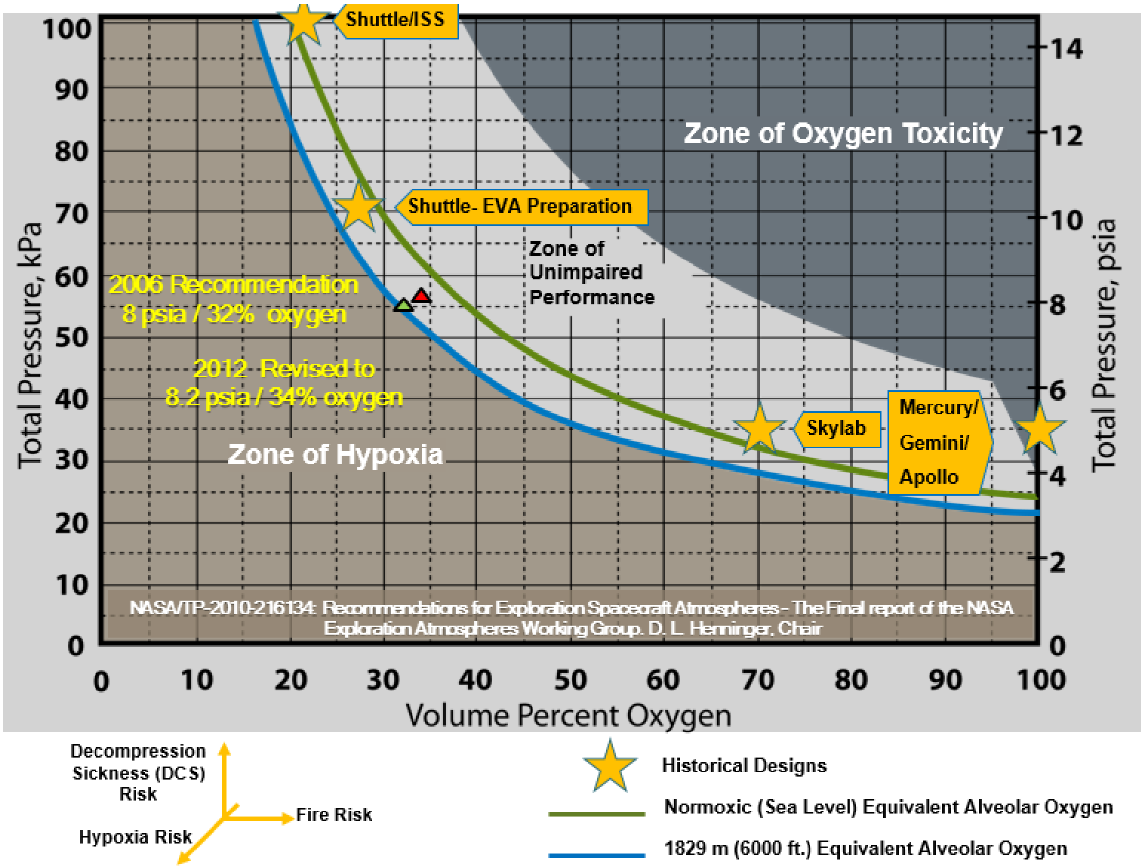


FIGURE 7.2.3-1 A HISTORY OF HSF: HABITABLE ATMOSPHERES EMPLOYED IN THE PAST

The following table is an example of the different vehicle operating and prebreathe pressures that have been proposed for human spaceflight recently with a 4.3 psia pressure during EVA. It describes some of the trades that need to be conducted going forward for habitat atmosphere, hardware, EVA prebreathe, and medical considerations (reference Figure 7.2.3-2).

Habitat Nominal Pressure	Pressure at prebreathe initialization	Duration at prebreathe pressure	µg EVA prebreathe duration estimation	Surface EVA prebreathe duration estimation	Hab A/L trades	Hab System trades	EVA trades	Med trades

14.7 psia
21% O2
	14.7 psia
	21% O2
		Constant	245 minutes	~420 minutes	Trade to prebreathe on mask or include separate module with minimal galley and WCS (for surface)
					• Prebreathe in integrated Next Gen A/L module with MAGs or separate w/o min. galley and WCS
					• Prebreathe in Next Gen A/L in separate module with minimal galley and WCS
						• Vent Next Gen A/L chamber air
						• Level of ISRU resupply vs logistics?
						• Reclaim A/L chamber air
						  • Into Hab (like ISS)
						  • Additional O2 tanks
							• Prebreathe protocol different from ISS
							• N/A, but long EVA prep
								• Crew injury, fatigue?

14.7 psia
21% O2
	10.2 psia
	26% O2
		< 12 hours	210 minutes	~2-3 times worse	Trade to go prebreathe on mask to separate module with minimal galley and WCS (for surface) or bring habitat down to 10.2psia/26% O2
					• Bring habitat down for prebreathe (Integrated Next Gen A/L module with MAGs or separate w/o min. galley and WCS)
					• Prebreathe in integrated Next Gen A/L module with MAGs or separate w/o min. galley and Waste Collection System (WCS)
					• Prebreathe in Next Gen A/L in separate module with minimal galley and WCS
						• Vent habitat air
						• Level of ISRU resupply vs logistics?
						• Reclaim habitat air
						  • Additional O2 tanks
						• Vent A/L chamber air
						• Reclaim A/L chamber air
						  • Into habitat (like ISS)
						  • Additional O2 tanks
							• Similar to ISS ISLE prebreathe protocol
							• N/A, but long EVA prep
								• ?

14.7 psia 21% O2	10.2 psia 26% O2	24 to < 36 hours	100 minutes	~2-3 times worse	• Same options as < 12 hours at 10.2 psia, 26% O2	• Same trades as < 12 hours at 10.2 psia, 26% O2	• Similar to Shuttle prebreathe flight rule	• ?

10.2 psia
26% O2
	10.2 psia
	26% O2
		≥36 hours	40 minutes	~2-3 times worse	• Integrated or separate module	• Vent A/L chamber air
						• Reclaim A/L chamber air
						  • Into habitat (like ISS)
						  • Additional O2 tanks
							• Similar to Shuttle prebreathe flight rule	• VIIP, hypoxia issues?

14.7 psia
21% O2
	8.2 psia
	34% O6
		≥36 hours	15 minutes	~2-3 times worse	• Bring entire habitat down for prebreathe (Integrated Next Gen A/L or separate w/o min. galley and WCS)
					• Prebreathe in separate Next Gen A/L module with MAGs
					• Prebreathe in Next Gen A/L in separate module with minimal galley and WCS
						• Exploration Atmospheres vehicle trades:
						  • Consumables, thermal, materials, avionics, food preparation
						• Vent habitat air
						• Level of ISRU resupply vs logistics?
						• Reclaim habitat air
						  • Additional O2 tanks
						• Vent A/L chamber air
						• Reclaim A/L chamber air
						  • Into habitat (like ISS)
						  • Additional O2 tanks
							• Prebreathe protocol different from ISS
							• PLSS packaging
							• PLSS OML
							• SIP
							• 8.2 psid PGS
							• Decreased MPT
							• Equipment vacuum certified
							• Short EVA prep
								• Decreased crew injury
								• Decreased crew fatigue
								• VIIP, hypoxia issues?

10.2 psia 26% O2	8.2 psia 34% O6	≥36 hours	15 minutes	~2-3 times worse	• Same	• Same	• Same	• Same
8.2 psia 34% O6	8.2 psia 34% O6	≥36 hours	15 minutes	~15 minutes	• Integrated or separate module	• Same	• Same	• same

FIGURE 7.2.3-2 HOST VEHICLE ATMOSHPHERE TRADES ASSUMING A 4.3 PSIA EVA PRESSURE

Furthermore, discussion should include the impacts of whether or not vehicles planned to operate with different atmospheres should all have the ability to operate at any of the planned mission atmospheres for commonality, as well as contingency situations.

7.2.4 Inflatable Portions of the Ingress/Egress Method

Inflatable structures technology utilizes high-strength fabric materials and internal pressure to create a stiffened structure that replaces traditional metallic primary structure. The flexibility of fabric structures allows them to be compact during launch and expanded in space, providing significant launch volume savings.

7.2.4.1 Inflatable Structures History

The use of inflatables in space has been worked since the 1960's for both habitats and airlocks. The first ever EVA was conducted by the Union of Soviet Socialist Republics (USSR) in 1965 using an inflatable airlock known as the Volga. This airlock was attached to the Voskhod 2 spacecraft, was successfully deployed, used once, and jettisoned after a historic spacewalk (Portree, D., et al. 1997).
Inflatable airlock development continued in the 1990's when NASA-JSC led an effort to demonstrate inflatable structures as feasible long-term pressurized elements with the TransHab project. The technology developed and pioneered during this project led to multiple patents and feasibility that inflatables could be used for large habitable structures (delaFuente, H., et al. 2000).

7.2.4.2 Current Inflatable State of the Art

In the early 2000's, Bigelow Aerospace used NASA support to continue development that eventually led to the successful flight certification, launch, attachment and deployment of the Bigelow Expandable Activities Module (BEAM) on the ISS in 2016 as shown in Figure 7.2.4.1-2 (Dasgupta, R., et al. 2014).

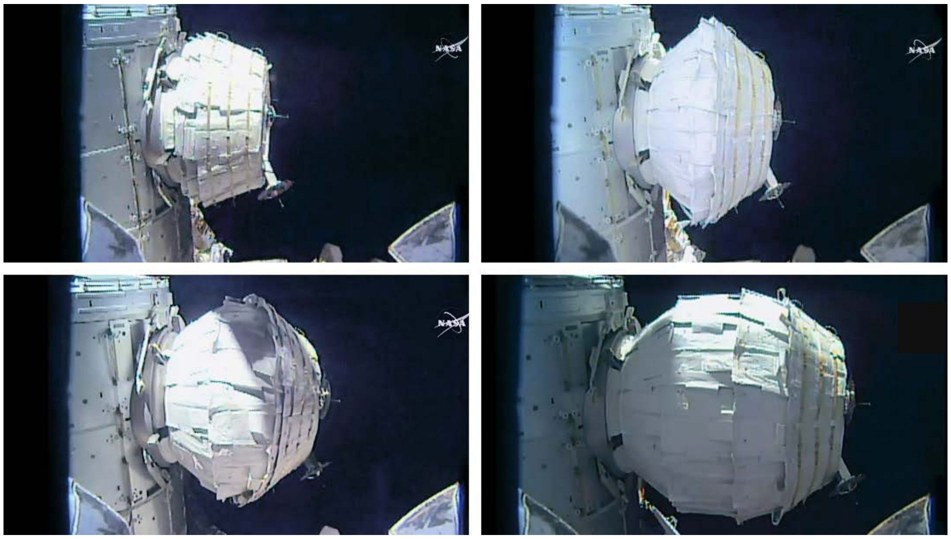


FIGURE 7.2.4.1-2 – BEAM MODULE DEPLOYMENT SEQUENCE

BEAM completed a successful two year evaluation period on the ISS, advancing the technology readiness level of a habitable inflatable module to TRL 9. It is considered a flight proven system and is currently used as a logistics module on the ISS.

Although BEAM is not an airlock system, the structural technology demonstrated could act as a baseline for the construction of an inflatable airlock system. Its current design poses limitations for EVA that would need to be addressed. The exterior of BEAM includes soft, fabric handrails meant for contingency EVAs, but can only be used for translation, does not allow for crew safety tethers, and does not include any worksites.

Inflatable and expandable airlock structures have undergone various detailed feasibility studies for over 15 years, most notably the Advanced Inflatable Airlock (AIA), Dual-Chamber Hybrid Inflatable Suitlock (DCIS), Minimalistic Advanced Soft Hatch (MASH), and Lightweight External Inflatable Airlock (LEIA). Through this time, full-scale articles have been built and pressure-tested, and mock-ups and demonstrators have been constructed and evaluated. The following sections are high-level summaries of these projects, and additional references are included for more detail.

7.2.4.3 Inflatable Development Work to Date

In 2001, the AIA concept was matured through requirements development, conceptual design, subscale and full scale engineering breadboards subjecting various test articles to deployment and pressure testing (Trevino, L., et al. 2002, 2003). These tests proved the feasibility of successful deployment and structural integrity of an inflatable crew lock. Figure 7.2.4.3-1 shows the fully-inflated pressure test articles as well as details of the latching and deployment systems.

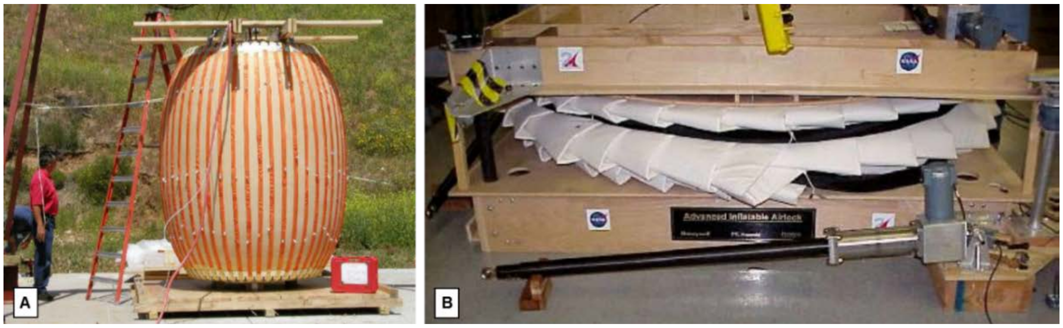


FIGURE 7.2.4.3-1 – A) AIA FULL-SCALE PRESSURE TEST ARTICLE AND B) LATCHING/DEPLOYMENT SYSTEM SHOWN IN PACKED CONFIGURATION

The 2017 LEIA effort advanced the design of an internal secondary structure and placement of handholds and foot restraints to enable hatch opening, closing and translation through the crew lock using a full scale mockup as shown in Figure 7.2.4.3-3. The results of these tests inform the volume required, hatch size, configuration and location of translation aids for crewmembers in a microgravity crew lock.

FIGURE 7.2.4.3-3 – LEIA SECONDARY STRUCTURE MOCKUP TESTING

7.2.4.4 Alternate Inflatable Concepts

In 2011, the DCIS was developed as a suitport-airlock with inflatable portions and meant as a planetary surface airlock concept. It utilizes three rigid bulkheads with dual chamber inflatables that are expanded to create additional volume as shown in Figure 7.2.4.4-1. The concept incorporates suitports into the middle bulkhead where one chamber is continuously pressurized and the second chamber is pressurized or at vacuum. A secondary structure is used to maintain structural capabilities in the depressurized chamber. This dual-chamber airlock allows for suit maintenance, dust mitigation, and compact packaging for transportation (Howe, S., et al. 2011).

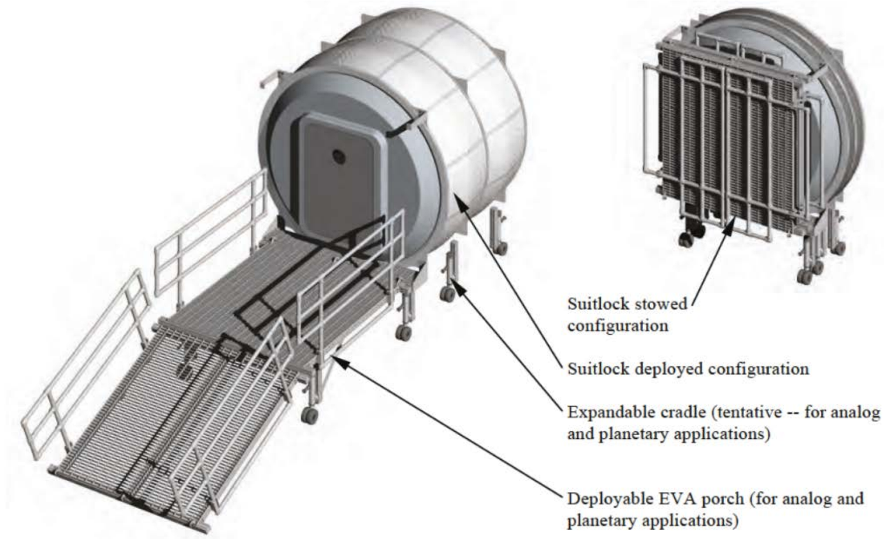


FIGURE 7.2.4.4-1 – DUAL CHAMBER INFLATABLE SUITLOCK CONCEPT

In 2014, the MASH project developed an ultra-lightweight airlock concept with a fabric hatch and airlock that utilized a unique pressure vessel shape to minimize structural load on the fabric material as shown in Figure 7.2.4.4-2 (Doggett, W., et al. 2016). The advanced concept uses a robotically controlled zipper-like latch and opening that is then peeled away to allow for crew egress/ingress.

FIGURE 7.2.4.4-2 – MASH AIRLOCK CONCEPT

Due to the novelty and uniqueness of this design, it offers a number of operational issues and concerns compared to traditional airlock systems. The hatch and sealing system would need to be redundant, reliable, and able to be controlled by a suited crewmember without extraneous force. A secondary structure would be necessary not only for structural stiffness, equipment mounting, and tethering, but to open and close the fabric hatch. Additional development is required to address these and other outstanding issues related to this design, but the mass and weight savings that it offers could provide EVA capabilities to a variety of spacecrafts with minimal costs.

Other concerns were noted during an EVA Office review of the Lightweight Materials & Structures Minimalistic Advanced Softgoods Hatch project in 2015:

- <u>Overall comment</u> - The idea of a soft hatch, although providing engineering optimization (lower mass, etc.) is worrisome from an operational standpoint since softgoods tend to have ‘memory’ in a weightless environment. It is unknown how this will be during pressurization/depressurization of air beams.
  - ‘Fighting’ this material memory, can quickly lead to fatigue, as has been seen when handling various large pieces of Multi-Layer Insulation (MLI) during EVAs on ISS
- Concerns with solution of using a zipper for sealing the soft-hatch
  - It looks very labor intensive from a crew fatigue perspective (specifically hands and forearms), as the crew would have to continually adjust their body position and how they are reacting the forces that are required to pull the zipper during both egress and even worse on ingress when the crew is fatigued from the EVA
  - Required forces that are easy to overcome in 1-g become exaggerated in 0-g, as the crew has to essentially double it to account for both the force to manipulate the hardware, as well as the reaction force to manipulation force
  - From a hazards perspective it seems it would be more likely to fail to properly seal.
  - Is every tooth required to properly connect?
  - Is there any redundancy, such as would be with multiple seals?
- Time required for operating (opening & closing) – impacts to emergency repress ability
  - How does pressurization/depressurization of the different air beams work? Does the crew control them?
- Recommend the open/closing motion be similar to ISS airlock, vs. a simple ‘door-hinge’ style motion
  - Rationale for this: a ‘door-hinge’ style motion will require depth to be added to the airlock that is equivalent to the ‘sweep’ of the hatch into the airlock
  - Rationale for this: a ‘door-hinge’ style motion requires crew to continually change their body position/location throughout the opening and closing motion, and if the hatch includes a fabric hinge, there will likely be ‘memory’ in the fabric that will have a neutral position that will need to be compensated for during manipulation (also need to consider the volume required for this manipulation and whether there will be enough to accommodate two crewmembers)

  - Benefit of a door-hinge like in the RS A/L is that it is a simpler design
- Performing regular EVAs from an inflatable would require the use of safety tethers (assuming no SAFER) to be able to withstand 220 lbf applied to the translation path used by the crewmember on the airlock and 200 lbf on all primary and secondary structure inside or near a translation path or worksite
- Worksites would be needed
- Hard internal structure would be necessary for hard mounting the UIA and interfaces to ECLSS recharge

In 2018, concepts focus on an inflatable crew lock-type structure attached to a rigid equipment-lock or habitat structure as shown in Figure 7.2.4.4-3. Since most of the SPCE items required are rigid components, a fabric structure cannot provide the capabilities of a full equipment-lock. The use of an inflatable as a crew lock, however, provides all the required capabilities for EVA operations.

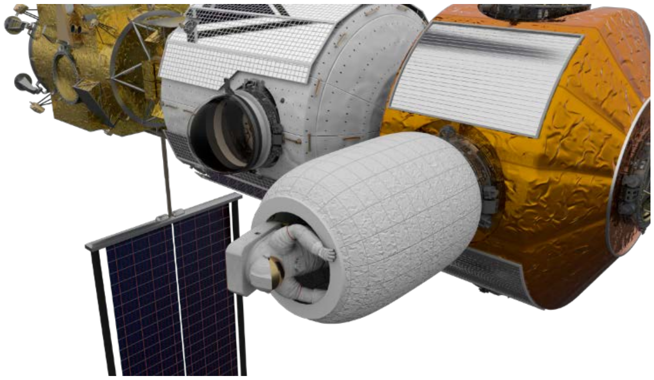
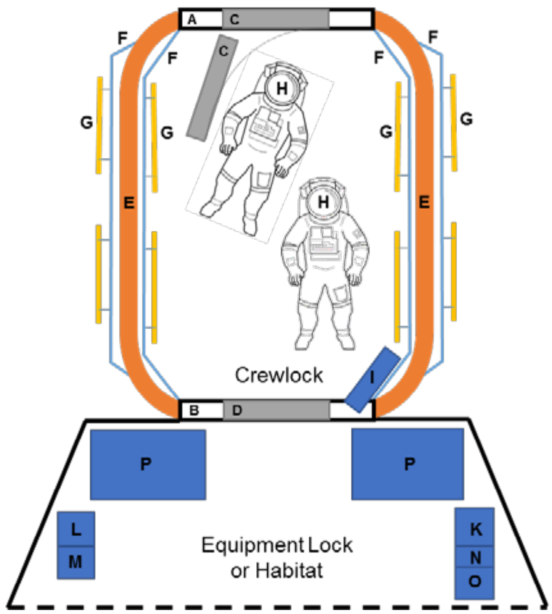


FIGURE 7.2.4.4-3 – INFLATABLE CREW LOCK CONCEPT

Since an inflatable module gets its stiffness from internal pressure, it needs a secondary structure to maintain the shape and stiffness of the fabric shell during depressurization. The secondary structure also provides support for handholds, tether points, workstations, cameras, etc. on both the interior and exterior of the crew lock.

The inflatable crew lock components are shown in Figure 7.2.4.4-4 with rigid bulkheads at each end of the structure. The use of a traditional, rigid EVA bulkhead meets thermal heating requirements and allows for any hatch design to be used with an inflatable shell. A rigid IVA bulkhead includes utility passthroughs for fluids and power, and an integrated UIA that is installed and launched inside the inflatable crew lock.



Crew Lock Components
A) Outer Bulkhead (EV Side)
B) Common Bulkhead (IV Side)
C) Extravehicular Hatch (EV)
D) Intravehicular Hatch (IV)
E) Inflatable Primary Structure
F) Secondary Structure
G) Translation Aids and Mounting (Internal & External)
H) Suited Crew Members
I) Umbilical Interface Assembly

Equipment Lock Components
J) IV Hatch
K) Power Supply
L) Battery Stowage
M) Battery Charging
N) In-flight Refill
O) Water Recharge
P) Don/Doff Assembly

NOTE: Image not to scale. Equipment lock component placement shown for reference only.

FIGURE 7.2.4.4-4 – INFLATABLE CREW LOCK CONCEPT WITH CONCEPTUAL COMPONENT PLACEMENT

Based on the work completed to date, an inflatable crew lock has been demonstrated to be feasible and is currently included in the trade space for potential alternative ingress/egress methods for deep space or planetary exploration.

7.2.5 Diameter of Module

Note: this section is primarily for suitport and rear-entry airlock concepts and does not apply to dual chamber airlocks. For an ingress/egress method on an internal bulkhead on a horizontal habitat, it has been shown that the diameter of a module can be driven by the ingress/egress method used and hatches needed. With suitport as the primary ingress/egress method on the Small Pressurized Rover (SPR), and based on older SIP assumptions, Figure 7.2.5-1 shows different diameter sizes with the two suitports on a bulkhead (Brand Griffin, Marshall Space Flight Center (MSFC), 2008, dimensions not to scale).

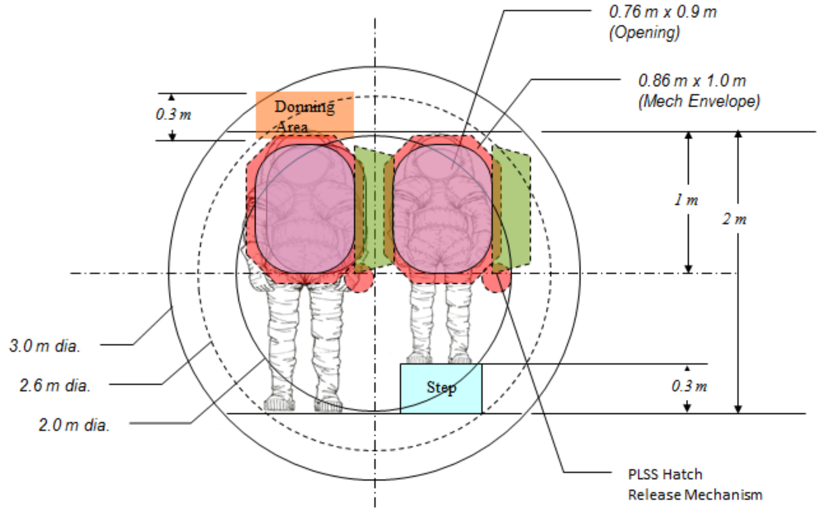


FIGURE 7.2.5-1 SUITPORT BULKHEAD (SPR APPLICATION)

With the rear-entry airlock or suitport-airlock options on a habitat, the bulkhead diameter must be larger in order to accommodate the addition of the internal hatch between the two suitports (reference Figure 6.2.4-2). This allows the crewmember to walk into the pressurizable volume shirtsleeve to perform maintenance on the front of the suits or transfer items between the pressurized volume and the habitat cabin.

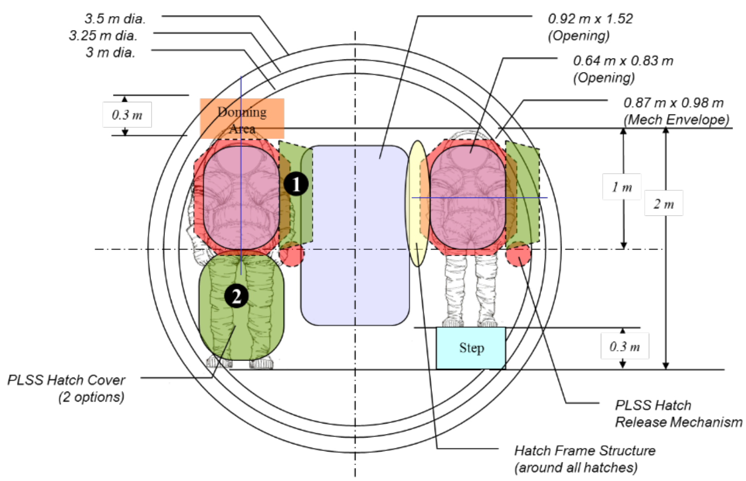


FIGURE 7.2.5-2 REAR-ENTRY AIRLOCK BULKHEAD (HABITAT APPLICATION WITH INTERNAL HATCH)

While a 3.5 meter diameter would help decrease consumables, first drafts of the concept have shown unacceptable interference between the opening of the vestibule hatch and the side wall. Two bulkhead designs were examined including a tri-planar and a planar bulkhead (Figure 7.2.5-3). Both were angled to facilitate donning. The tri-planar bulkhead helped to decrease internal volume but made the interference constraint much worse and ingressing at an angle going backwards adds to the operational difficulty. It was recommended that further work be done to look at the right diameter, mass, and volume to find out if objectionable interference could be eliminated.

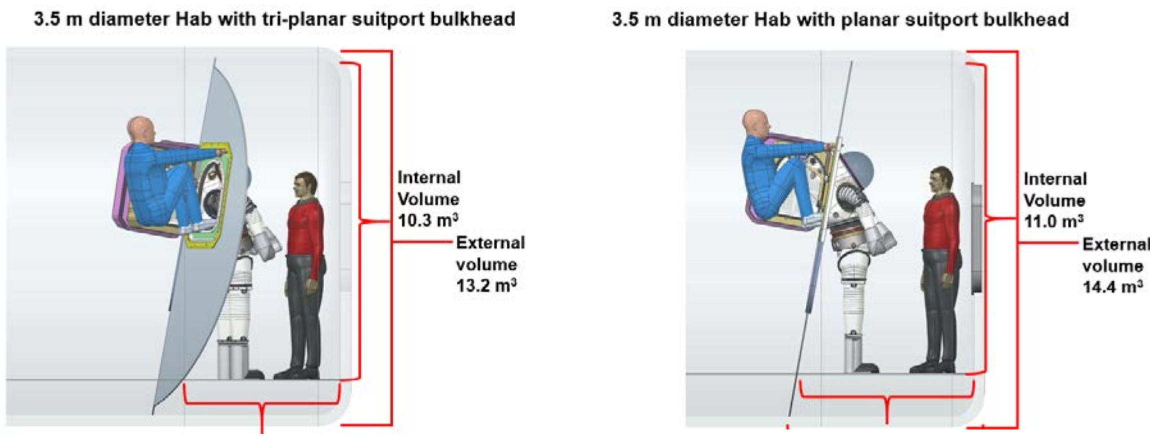


FIGURE 7.2.5-3 REAR-ENTRY AIRLOCK BULKHEAD (ANGLED 3.5 M DIAMETER TRI-PLANER AND PLANAR BULKHEADS)

Although it has not been sized yet and has trades of its own, the hatch within a hatch idea has been discussed as an option to allow the internal hatch access while keeping the diameter of the module down.

7.2.6 Hatches

There is a large historical dataset available on hatches, and only a small portion is described within the scope of this document. The following sections will focus on EVA-compatible hatches and what direction they open, what size they need to be to support suited pressurized crewmember ingress/egress for both microgravity and surface operations, primary and secondary hatch requirements, and discussion of having a “hatch within a hatch” for a specific architectural concept.

In addition to a suited crewmember being able to exit the hatch, depending on the operational scenario and task, you may also need to move large ORUs or other equipment through the hatch, and may need to size the hatch accordingly.

7.2.6.1 Inward-opening vs. Outward-opening Hatches

Referencing Worldwide Spacecraft Crew History (NASA/TP–2010–216131, 2010):

"The future design of human spacecraft crew hatches will require a trade study to weigh the risk of designing an inward-opening hatch as compared to an outward-opening hatch. A rigorous risk analysis of conditions or hazards that can potentially create a need for emergency crew egress or emergency ingress of ground personnel for the pre-launch and post-landing time periods must be performed. To mitigate the crew safety hazard, a single unified (pressure seal and thermal protection) hatch for quick outward opening is preferred; reference the Apollo Crew Module (CM) and shuttle orbiter crew ingress/egress hatch. This would be compared to a risk analysis of long mission time exposure to space vacuum in which the crew safety hazard is cabin depressurization/loss of cabin atmosphere due to crew hatch seal leakage or failure. To mitigate the crew safety hazard related to depressurization, an inward-opening and pressure-sealing hatch is preferred, as cabin pressure tends to seal the hatch vs. an outward opening where cabin pressure tends to open the hatch. This may result in an inward-opening pressure-sealing hatch and an outward- opening thermal protection hatch, as the Russians designed for the Buran. An earlier look at the performance history of spacecraft hatches has shown that when the crew hatch is also the EVA hatch, an inward-opening pressure-sealing hatch is preferred."

For safety purposes, those hatches within the cabin and the ingress/egress method that are not otherwise cycled on a launch pad for emergency egress would most likely be inward-opening. The size of the hatch will also be of concern as there is a minimum dimension that should be utilized on the vehicle for a crewmember to safely translate through during an EVA.

7.2.6.2 Hatch Size in Microgravity

Hatch sizes were evaluated by Computer Aided Design (CAD) models in 2015 using the Z-2/PLSS 2.5 model showing static egress (does not take into account that the crewmember can change position to fit through an opening or soft goods shape change) through the U.S. crew lock, the Russian airlock Pirs, the ability to fit through the FGB bulkhead hatch, and IDA/NDS. The model used comes with the following caveats:

- SAFER, Display Control Unit (DCU), Modular Mini-Workstation (MMWS) or tools are not attached
- Boots, a full arm assembly, and gloves are also not currently in the Z-2 CAD model
- The Hard Upper Torso (HUT) in the CAD model is not the largest size HUT expected for the Advanced Extravehicular Mobility Unit (AEMU).

For current microgravity operations, the ISS A/L EVA hatch for ingress/egress of the crew is a 36 in. x 40 in. diameter “D” hatch. (reference Figure 7.2.6-1, courtesy NASA Imagery Online iss028e016325):

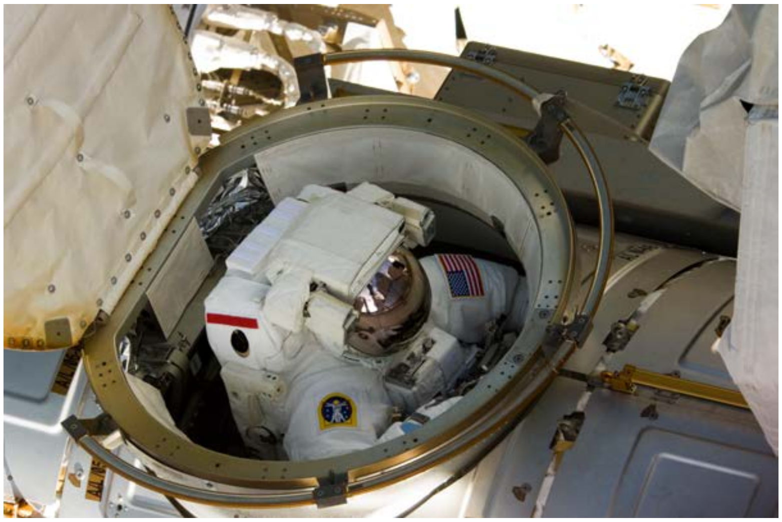


FIGURE 7.2.6-1 ISS AIRLOCK EVA INGRESS/EGRESS HATCH WITH EMU (MICROGRAVITY EVA)

With the mini-workstation and tools attached, clearance is limited for the EVA crewmember to exit the ISS EVA hatch. When exiting the airlock, the PLSS should align with the D-flat to maximize clearance on the front of the suit for the MMWS and DCU.

The Z-2/PLSS 2.5 assembly should fit through the U.S. and Russian airlocks (Pirs) even when a SAFER, DCU, and MMWS are installed as shown by CAD.
Pirs EVA hatch is 1m (39.37 inches) in diameter (not a D-flat style airlock hatch). Given the clearance seen for Z-2 in the U.S. airlock, the suit should have no trouble clearing the Pirs EVA hatches

However, the Functional Cargo Block (FGB) bulkhead to Pirs docking module is about 800mm (31.49”) in diameter. The Z-2/PLSS 2.5 will not fit through the FGB bulkhead once the SAFER, DCU, and Mini-workstation (MWS) are installed. Transfer through the FGB bulkhead may be possible if the MWS is not installed, but this needs to be demonstrated by a physical test as the CAD model is not dynamic and the clearances are too small to determine if it is possible. It may be difficult for the crew member to pull themselves through such a small passage way, especially if operating at a higher suit pressure. The legs will interfere if the position of the suit is not changed and the crew member will need to roll forward out of the hatch. The CAD shows there is less than an inch between the PLSS and the hatch (again, the suit model is not the largest size) in the following figure.

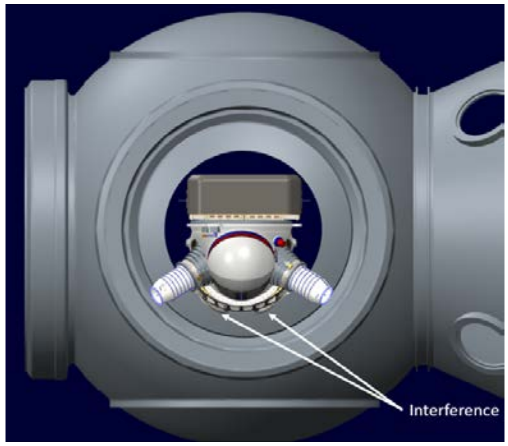


FIGURE 7.2.6-2 FGB 800MM HATCH INGRESS/EGRESS HATCH WITH Z2 CAD (MICROGRAVITY EVA)

Ideally, pressurized suited crew would be able to translate through spacecraft docking collars. This capability would also need to include transfer of an incapacitated crew through the docking collar. However, the International Docking System Adapter (IDA) Standard Pass-Through requirement is 31.5 inches inner diameter of the petals (similar in diameter to the FGB hatch) and is expected to be used for future Exploration-class vehicles (Reference SSP 50933, IDA to ISS and Visiting Vehicle IRD, Soft Capture Ring Dimensions). See figure 7.2.6-3 for the clearance through the IDA petals. While the crewmember can possibly maneuver through the petals, especially if one of the petals could be removed, the tunnel diameter would still be 800 mm when docked.

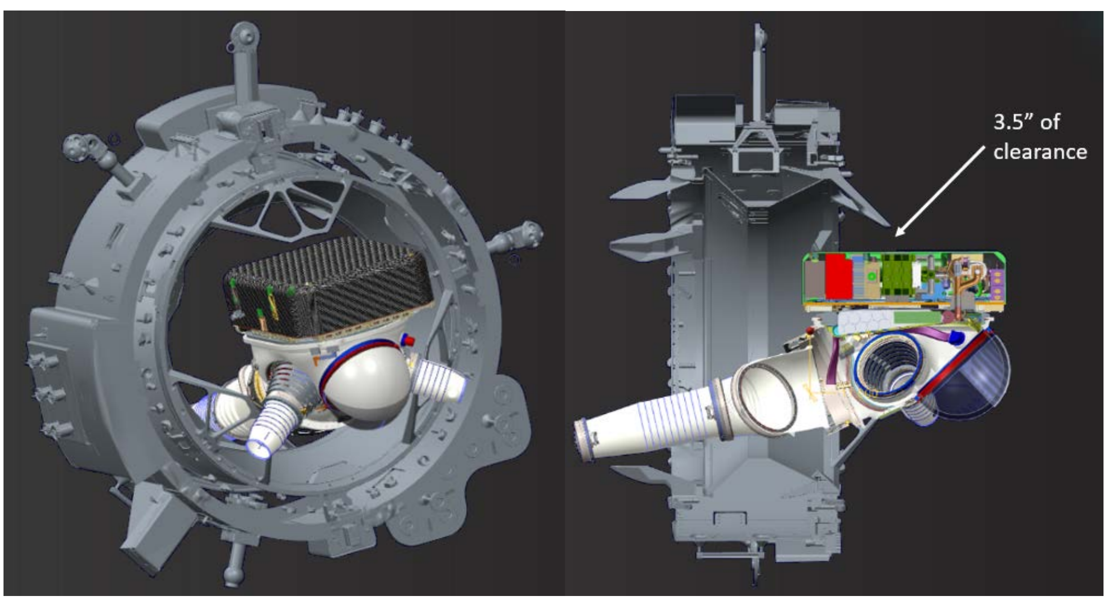


FIGURE 7.2.6-3 IDA INGRESS/EGRESS HATCH WITH Z2 CAD (MICROGRAVITY EVA)

Again, if adding in the DCU and MMWS, this could be an issue. As shown by the FGB hatch CAD, there is not enough clearance through an 800 mm hatch.
The current hatch assumption held by the EVA community is discussed in the EVA Assumptions for Future Vehicles section of this document.

Orion side hatch operations have also been discussed and evaluated in the Neutral Buoyancy Lab (NBL) in 2011 (reference EVA Systems Project Office (ESPO) Test 8: Joint EVA NBL Orion Mackup (JENOM) Neutral Buoyancy Laboratory Test Report). While it is possible to fit through the side hatch with an EMU, changes would need to be made both to Orion and the xEMU to enable EVA capability. Currently, Orion is not considered EVA compatible.

7.2.6.3 Hatch Size for Surface Operations

For exploration vehicle assets that include surface operations with any significant quantity of EVA's, the ingress/egress hatch size is assumed to be large enough to support the upright stature of a walking person. The hatch size recommended is 40 in. x 40 in. (0.92 m. x 0.92 m.) minimum up to ~40 in. x 60 in. (0.92 m. x 1.52 m.) depending on the frequency of the EVAs. Note that this assumption could be deferred on an architecture with very, very few EVAs per mission (such as Apollo), in which case it is likely acceptable that smaller size hatches may trade favorably even if they require somewhat less convenient postures such as crawling as did the Apollo Lunar Lander EVA hatch. In this case, the mobility to perform such tasks could impact the suit.

7.2.6.4 Secondary Hatch Requirement

While not all vehicle or ingress/egress designs require both a primary and a secondary EVA hatch, an analysis of failure modes could reveal the need when coupled with program-specific choices for human rating and redundancy/fault tolerance strategies. Fault tolerance should be included in detailed mechanism designs; however, there are some failure modes (repress failure) that may not be able to be mitigated without adding a secondary hatch.

Hatches must allow a pressurized suited crewmember to exit and enter the vehicle. Sufficient access and free volume will be needed to allow the crew to perform nominal EVAs, as well as contingency ingress operations such as a hatch failure or a failure to repress. For ISS, this is resolved by providing a separate crew and EVA equipment lock which can each function as an airlock in the event of a hatch or repress failure. Other solutions might include having a secondary hatch and bringing the cabin down to vacuum to allow the crewmembers to transfer into the cabin and repress the cabin. Having an inner secondary hatch along with suitport hatches inside of a suitport-airlock allows the crewmember to either enter the cabin shirtsleeve as they doff their suits through the bulkhead, or could allow the crewmember to transfer through the secondary inner hatch.

7.2.6.5 Hatch within a Hatch

Note: this section is primarily for suitport and rear-entry airlock concepts and does not apply to dual chamber airlocks. For the hatch within a hatch concept, the potential benefits may be outpaced by the inherent complexities (see graphics below, courtesy of Brand Griffin 2008, notional dimensions) (reference Figure 7.2.6-2 and Figure 7.2.6-3 in the blue box). Vehicle services described in Section 3.1 have to be integrated with the bulkhead/hatches to reach the PLSS located in the inner vestibule hatch. This will allow for recharge of the suit between EVAs which could add to the complexity of the umbilicals and running lines around the hatch openings.

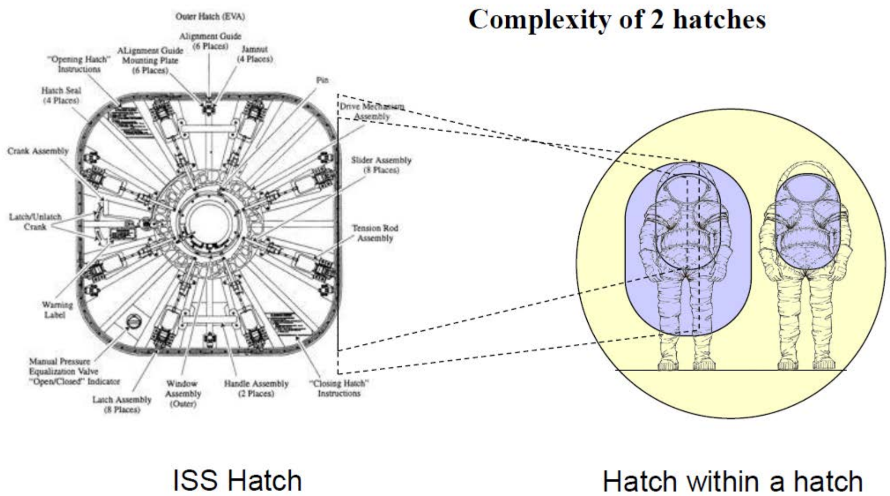


FIGURE 7.2.6-2 COMPLEXITY OF HATCH WITHIN A HATCH

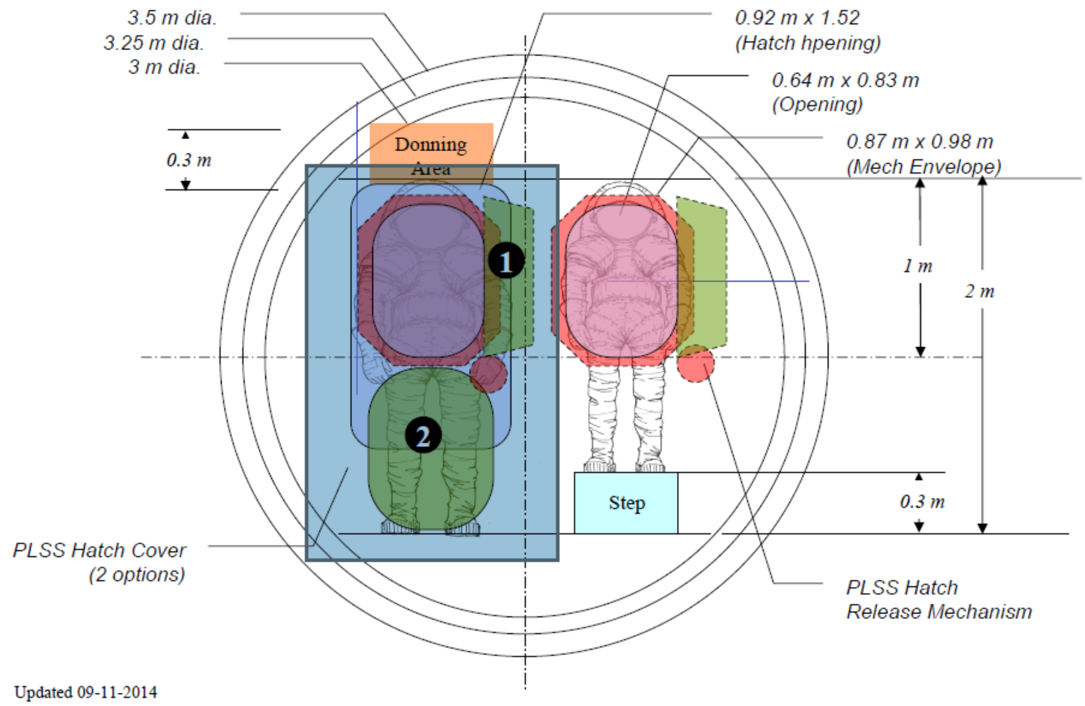


FIGURE 7.2.6-3 REAR-ENTRY AIRLOCK BULKHEAD (HABITAT APPLICATION WITH INTERNAL HATCH WITHIN A HATCH)

7.2.7 Dust Mitigation/Planetary Protection Differences between Ingress/Egress Concepts

Dust mitigation can refer to either the lunar surface or the Martian surface and is an important aspect for both. Planetary Protection is particularly important for the Martian surface and concerns both forward and backward contamination. Forward meaning contamination of humans on the Martian surface. Backward meaning bringing Martian microbes back to the Earth. So far, the Planetary Protection Office does not have specific requirements, but instead understands the operational control of defining special regions that the humans cannot enter. This will be better understood once a landing site is determined and the degree of particle transport on the Martian surface is further understood. While Planetary Protection is not necessary on the Earth's moon, the lunar surface would be a good analog to demonstrate a "layered engineering defense".

For the lunar surface, only dust mitigation is of moderate concern due to respirable complications. The following is an example standard derived from NASA-STD-3001, Volume 2, V2 6053 in consideration for the entire system between the vehicle, ECLSS, and crewmembers:

- The system shall limit the levels of lunar dust particles less than 10 μm in size in the habitable atmosphere below a time-weighted average of 0.3 mg/m3 during intermittent daily exposure periods that may persist up to 6 months in duration.
    - *Rationale: This limit was based on detailed peer-reviewed studies completed by the Lunar Atmosphere Dust Toxicity Assessment Group (LADTAG) and is specific to the conditions relevant to the lunar surface, i.e., this standard would not necessarily be applicable to other missions. The standard assumes that the exposure period is episodic and is limited to the time before ECLSS can remove the particles from the internal atmosphere (assumed as 8 hours post-introduction). Although the standard is being conservatively applied to all inhalable particles (all particles ≤10 μm), it is most applicable to dusts in the respirable range (≤2.5 μm) that can deposit more deeply into the lungs. Studies show that the particle size of lunar dust generally falls within a range of 0.02-5 μm.*

An example of a system collaboration is discussed below.

Certain ingress/egress methods provide dust mitigation techniques by keeping EVA suits on the opposite side of the bulkhead from the habitable environment, while others may amplify dust contamination. For instance, a traditional airlock allows the crewmember to doff their presumably dusty suit on the don/doff stand and then translate/walk through the dust that was just carried in on the suit. On a subsequent EVA, crewmembers must reverse this path and again translate/walk in their undergarments/Liquid Cooling Ventilation Garment (LCVG) through the dust prior to donning the suit on the don/doff stand. This architecture would fundamentally promote dust contamination issues.

To address this concern, one possible solution utilizes a “Layered Engineering Defense” plan (Wagner, S. 2014) which utilizes “layers” to help mitigate the effect of dust on the suit materials, control the transfer of dust on the suits, reduce or eliminate forward and backward contamination to the crew and habitation, and minimize cleaning and protection (interior and exterior) and the use of air quality contamination zones. The space suits need to be brought inside a habitable volume for nominal and contingency maintenance, which will introduce some amount of dust into the habitable volume. The operations of the removal of dust from the suits will be a multi-phase operation to limit dust introduction into the suits and into the crew cabin. Tools and samples could also introduce dust into the airlock. Stowage/containment and cleaning of these items is important in addressing dust mitigation. Operational controls and air quality zones utilize ingress/egress methods that will mitigate dust transfer into the cabin, (i.e. rear-entry airlocks, suitport-airlocks, and suitports). An ingress/egress method can also provide particulate mitigation and backward and forward planetary protection by donning/doffing the rear-entry EVA suit through a bulkhead, such that the crewmember does not translate through the dust during vehicle ingress and don/doff. Cabin filtration is necessary on the assets/habitation for dust mitigation and planetary protection. Ingress/egress methods such as rear-entry airlocks/suitlocks and suitport-airlocks could include a large enough chamber to perform the maintenance in or a secondary chamber or mud room to further contain contamination and increase air quality as the crewmember translates to the cleanest areas of the vehicles, such as habitats, pressurized rovers and ascent vehicles.

With a suitport, suitport-airlock, or rear-entry (suitlock) the majority of dust remaining on the suit will be kept on the other side of the habitation zone. Depending on the design of the habitat, the ingress/egress method can add one or two zones to keep the contamination out of the crew quarters (reference Figure 7.2.6-1). Below is an example of a layered engineering defense plan (tailored for EVA); other protocols can be followed. These details and operational concepts are in-work.

- 1st Layer – Mission Architecture Design
  - Avoidance of Special Regions (defined within X radius of lander/habitat prior to the mission)
- 2nd Layer – Hardware Design
  - EVA Suits will leak/vent – Engineering limits must be understood and intentionally accounted for
  - Sample tool collection/containment
- 3rd Layer – Operational Design
  - Suit ingress *directly* to habitable volumes should be eliminated to extent possible, examples of this include the ingress/egress method (rear-entry suit don/doff through bulkhead)
  - Sampling Protocols limit inadvertent contamination
  - Leaving EVA suits on the surface prior to ascent to “break the chain” of contamination
- 4th Layer – Contamination Control
  - Conduct verifiable decontamination of EVA hardware on a regular interval
  - Conduct Exterior and Interior Cleaning
  - Utilize Air Quality Contamination Zones

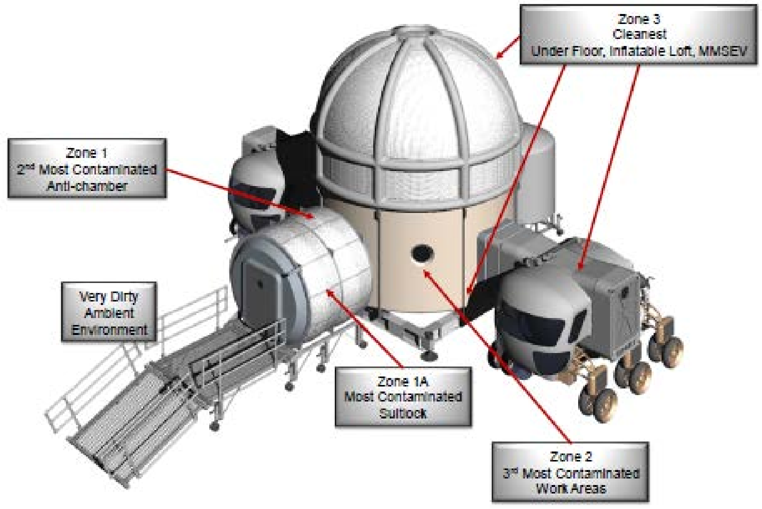


FIGURE 7.2.7-1 LAYERED ENGINEERING CONTAMINATION ZONES

While suitports, suitport-airlocks, and rear-entry airlocks keep the suit outside of the crew cabin, the PLSS is still on the inside of the cabin vestibule door. Dust mitigation tools such as brushes attached to the vestibule door, sealing mechanisms around the PLSS on the vestibule door to keep the dust inside that inner volume, and vacuum/filtration for the vestibule volume need to be investigated.

Ingress/egress methods may be the best option for minimizing dust inside of the cabin for the rover; however, exploration EVA suits must still be brought inside a pressurizable volume for suit maintenance on missions longer than 30 days in duration. It is assumed that a rear-entry airlock or suitport-airlock will be on the long duration habitat; however, it should be demonstrated how much this helps keep dust out of the habitable volume compared to the regular airlock (e.g. walking through the dust after every EVA). Dust modeling/testing should be performed to show the differences between using a concept that keeps suits on the opposite side of the bulkhead and heritage airlocks.

Multiple chambers such as the dual chamber airlock can also be utilized, but may require more cleaning and innovation to help keep the dust from getting inside the suits.

7.2.8 Volume Studies and Suit Maintenance

Volume studies have been done in the past for both a surface airlock and don/doff volumes. New volume studies should be performed to further understand the amount of room needed inside of an ingress/egress method to facilitate suit maintenance, allow enough room for tools, and hatch swing.

The following is an overview of EVA tasks and volume:

- Internal task volumes are mission architecture dependent
  - Purpose of EVA (contingency vs. nominal)
  - Destination class (type of suit) – focus on µg first
  - Contingency scenarios (secondary ingress, number of chambers)
- Ops Con, architecture and risk dependent
  - EVA assumes a secondary ingress – this is usually dual chamber configuration (similar to ISS equipment lock and crew lock)
- Permanent Hardware:
  - Volume for EVA support equipment (already have ISS SPCE)
- PLSS recharge equipment (power, communications, umbilical interface panel, etc.)
- ECLSS consumables and plumbing (not included in EVA System volumes)
- Some of the following tasks can be performed in the same volume:
  - Volume for 2 crewmembers to don/doff
- Assume unassisted (possibly third IVA crewmember support)
  - Volume for prebreathe
- Duration dependent (assume shared location with don/doff)
  - Volume for suits, tools, logistics and spares stowage
- Mission duration dependent (number of suits, how suits are stowed, amount of logistics needed based on usage exceeding limited life, sparing philosophy)
- Mission objectives dependent (science, suit maintenance tools, vehicle maintenance tools, dust mitigation tools)
  - Volume for in-flight maintenance
- Mission duration dependent
- Planetary Protection needs (partition, chamber, etc.)
- Suit architecture dependent (ORU level)

In any airlock, the don/doff volume needs to be considered to accommodate self-donning for two crewmembers. The volume in front of the suit needs to be large enough to accommodate a crewmember standing/kneeling in front of the suit to perform suit maintenance. The overall volume of the pressurizable area needs to be able to accommodate a crewmember and an incapacitated crewmember. The following is an overview of volumes needed based on a 10 EVA assumption:

- Interface/Volume to Don/Doff Suits (EVA prep/post servicing)
  - It is assumed the Equipment Lock portion will be used to don/doff suits potentially with a third IV crewmember assisting (dual chamber airlock)
  - Minimum ~3.5 m^3 assuming serial donning (~7 m^3 for simultaneous donning not including 3rd crewmember)

- Volume for EVA Stowage
  - Stowage volume for 3 suits (bundled similar to stowed EMU) = ~1.75 m^3
  - Some of this volume can be combined with the Volume to Don/Doff Suits
  - Trade available to stow EVA hardware in locations other than Airlock
- Volume for permanent support hardware = ~1.1 m^3
  - Most of this equipment would be located in the Equipment Lock
- Volume for logistics and tools = ~2.3 m^3
- Vehicle Egress/Ingress (hatch size)
  - 1000 mm clearance in projection (for microgravity)
- Volume for spares and additional logistics are TBD depending on mission duration and failure modes and component life
- Volume for ORUs and/or samples are TBD

7.2.8.1 Don/Doff Volume estimate

Estimates for a pressurized suit from CxP (not don/doff volume) was bookkept as 2.2 m (H) x 1.0 m (W) x 0.95 m (D). From past studies performed in a reduced gravity flight, a don/doff volume was estimated (reference Constellation Space Suit Element Engineering Memo EM-CX-Suit-09-0047); however, with the addition of including the head room of about 12 to 14 inches for rear-entry donning and room leg room, a new estimate has been formulated of 2.36 m (H) x 1.55 m (W) x 0.84 m (D) (see Figure 7.2.8-1):

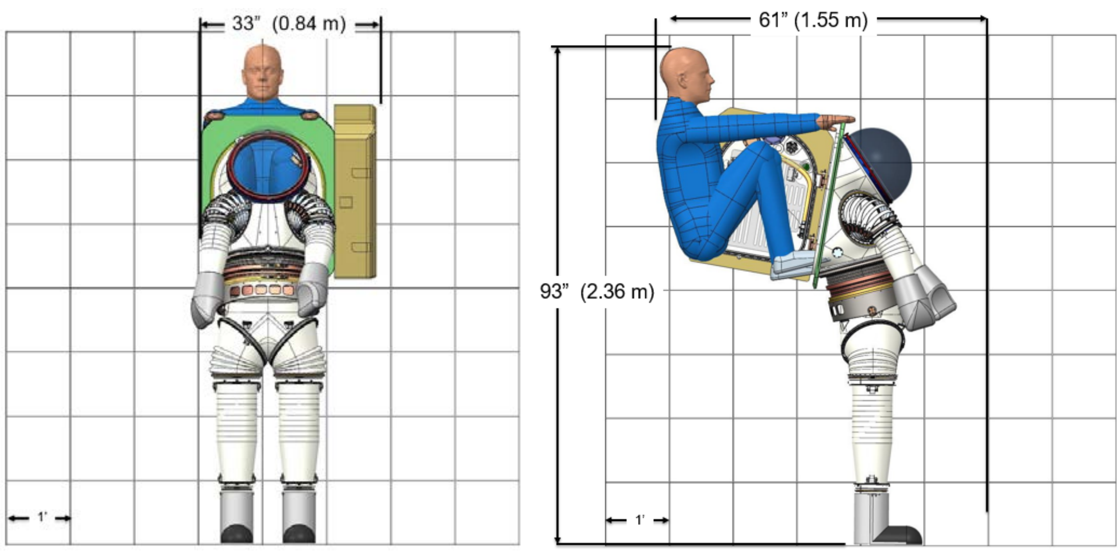


FIGURE 7.2.8-1 DON/DOFF VOLUME ESTIMATE

7.2.8.2 Suit Maintenance

Suit maintenance is performed on SoA EMUs on the ISS. For instance, the Fan Pump Separator (FPS) Remove and Replace (R&R) takes place in the ISS equipment lock, but it has been reported that there is more room and better hand holds in another module. There is not a dedicated suit maintenance area on the ISS; however, maintenance can be performed to the suit while it is on the donning stand. Most suit maintenance (especially refurbishment and recertification) is performed in facilities on the ground with test fixtures, clean rooms, and a multitude of tools. Transitioning from the way things are done today to on-orbit, long-term suit maintenance in a dusty environment will be very challenging. Failure modes and end of life cycles/testing need to be well understood for a new exploration suit to compile a complete list of services, maintenance, logistics, and spares needed for each mission. Current operations concepts assume pressurized rovers and habitats; however, suit maintenance cannot be fully performed on a pressurized rover due to their current suitport configuration. Only maintenance on the PLSS and whatever may be within reach of the inside of the PGS can be performed from the inside of the cabin while the rest of the suit is on the other side of the bulkhead. A pressurizable volume is necessary to bring suits inside for nominal suit maintenance such as repairs, sizing, etc.

Prior to entering the pressurizable volume, the suit is cleaned to the extent possible to bring in as little dust as possible. Basic inspection and cleaning operations are conducted within the pressurizable portion of the airlock and more extensive repair is conducted in the habitat general maintenance area if necessary. Umbilical interface panels should be located where suited crewmember operations occur.

In order to have the volume to perform suit maintenance in front of the suit, an initial assumption was that 1.22 meters was needed between the bulkhead and the outer bulkhead. This number could be optimized and will need to be refined through testing.

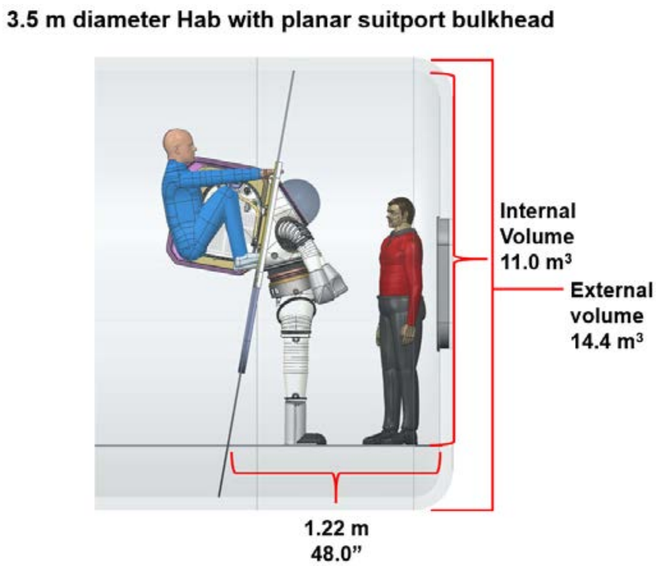


FIGURE 7.2.8-2 PLANAR BULKHEAD WITH 1.22 METER CLEARANCE

There has also been discussion of a mudroom. This adds volume, mass, and consumables; however, if the trade to go with a separate module for the habitat proves optimal, then the extra area could be used as a general maintenance area and an extra zone for dust mitigation assuming equipment is properly cleaned. See figure below.

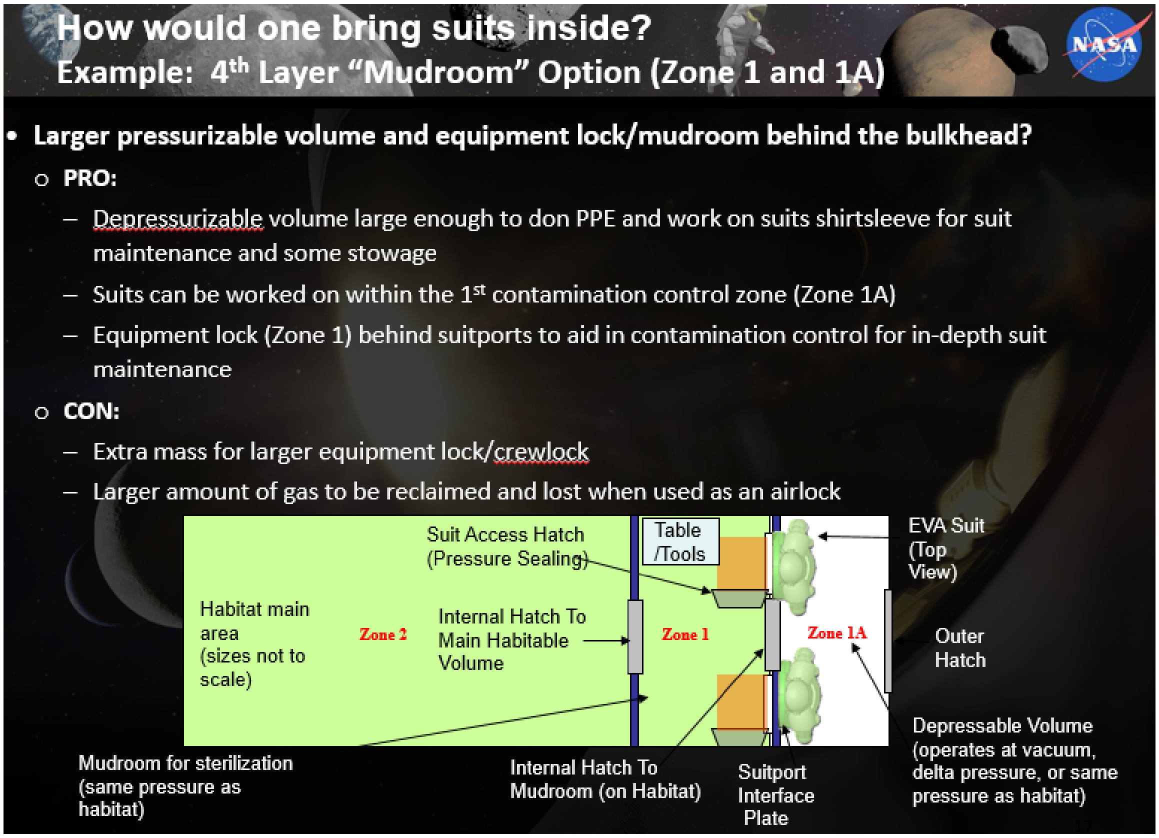


FIGURE 7.2.8-3 "MUDROOM" EXAMPLE

7.2.9 Incapacitated Crewmember

It is required to protect for the scenario where a crewmember may become incapacitated during EVA operations (microgravity and surface) as outlined in NASA-STD-3001 Volume 2, NASA Space Flight Human-System Standard Volume 2: Human Factors, Habitability, and Environmental Health. Incapacitated pressurized-suited crewmembers may be unable to ingress the vehicle on their own and may require assistance from a second crewmember. This may include ingress after an EVA, ingress/egress to/from the vehicle during an EVA, or any vehicle or module to which the vehicle is docked. The worst case scenario is always the pressurized suited crewmember as it involves the volume within the vehicle to perform the assisted task, hatch opening size and operation, as well as the external translation path and mobility/stabilization aids. Removing an incapacitated crewmember from a rear entry suit could be challenging and could require extra volume in the airlock, extra support structure, or possible tools to assist the crewmember inside as well as removal from the suit. The volume in any airlock option will need to take into account room for an IV crewmember to assist with rescue and suit doffing of an incapacitated crewmember.

All ingress/egress methods will need to allow for incapacitated crewmember operations. Each mission will be evaluated as the architecture and ops cons are defined.

7.2.10 Add-on to ISS and Integration

The Near Term DRM study determined that adding a suitport demonstration onto a new habitat module project, whether as an add-on, or as integrated onto the module, could be beneficial on the ISS. Testing another module with exploration atmospheres on the ISS has increased safety due to the availability of the ISS Joint A/L as a backup in case of contingencies. The ISS also has berthing installation capability with the Space Station Remote Manipulator System (SSRMS). Testing on ISS would avoid the need to design a vehicle to be used in cislunar space that is suitport compatible. The idea of adding the demonstration to ISS has been viewed as significantly challenging due to incompatibilities with existing airlock hardware, as well as the pressure differential and flammability concerns of integrating the module with the ISS, for example:

- Integration with ISS has not been formally assessed (ECLSS, power, communication/avionics, port availability, etc.)
- Materials testing at the maximum O2 concentration (~35%) as opposed to the 30% O2 (ISS A/L O2 compatibility, Flight Rule B17-3) would need to be looked into further
- Most of the same consumables used by the ISS EMU would be used by the EVA suit interfaces
- The ISS A/L interfaces are currently being updated to enable 3000 psi O2 capability

The need to determine what should be tested on the ISS is limited by schedule with current extension to 2024 and a potential extension to 2028.

As opposed to testing an alternative concept at ISS, it has been proposed to perform limited exploration atmospheres studies on ISS to determine alterations to physiological parameters, such as hematologic, immunologic, oxidative stress, visual impairment, and cognitive function, from reduced gravity exposure to mild hypoxia. Potential ISS issues were discussed along with draft test procedures and a list of impacted flight rules.

7.3 SUIT vs. VEHICLE SUITPORT OPERATIONS

Note: this section is primarily for suitport concepts and does not apply to dual chamber airlocks.

With future assets currently undefined, a study of some of the functions that are currently a burden on the suit can be placed on the vehicle as opposed to adding mass to suit (affects CG and mobility). For instance, suit access hatch open-close mechanism, PLSS rotation-translation, pressurization, ventilation, water circulation, dust mitigation, and environmental protection could be alleviated by exploration assets (TDS 1228 CSSS-T-010 RAC02 – Suitport Requirements Assessment).

7.3.1 Pressurization, Suit Access Hatch Open-Close, PLSS Rotation-Translation

Pressurization/depressurization of the suit and volume between the vestibule and the suit hatch/PLSS is a very important step in the procedures before the crewmember dons/doffs the suit. While the suit is unoccupied and stowed on the suitports, the suit is kept at 0.9 psid to keep it thermally conditioned. For the suitport concept, there may need to be extra thermal conditioning inside the cabana or environmental cover protecting the suits.

When the crewmember is ready to prepare for an EVA, the suit is brought up to cabin pressure at 8.2 psi, such that the suit is at 8.2 psid to vacuum. While the suit access hatch/PLSS and the vestibule hatch are still closed, the volume between the vestibule hatch and the suit access hatch/PLSS is assumed to remain at cabin pressure to enable PLSS access while the crewmembers are on the inside of the cabin. Equalization valves must be in the architecture to equalize the pressure between the three volumes. The crewmembers are then ready to ingress their suits and close the hatches. There can be a mechanism on the vehicle allowing the crewmembers to close their suit access hatch and rotate/translate/latch the PLSS to the suit and close the vestibule hatch. Once the crewmembers have completed a short prebreathe while performing suit checkouts, the volume between the vestibule hatch and the suit access hatch/PLSS is brought down to vacuum.

As discussed above, the suit is kept at 0.9 psid to keep the suit thermally conditioned while it is on the suitport and unoccupied. Previously, this implied that the suit primary regulator was constantly operational; however, there could be a regulator between the vehicle services and the suit which allows the burden to be transferred to the vehicle.

It is reasonable to assume that the higher the delta pressure across the suit, the higher the leakage rate. Keeping the suit at a delta pressure also causes suit leakage. In the past, suit leakage calculations were performed assuming the suit was kept at 8 psid, which was assumed to be the maximum delta pressure of the suit. This should be recalculated using the minimum delta pressure (this is currently assumed to be 0.9 psid, which needs to be verified) to show the difference in consumables loss.

7.3.2 Ventilation and Water Circulation

While the suit is unoccupied and stowed on the suitports, it was assumed that the PLSS pump was operating continuously to prevent the water lines from freezing, but this could be performed by the vehicle. If the umbilicals are on the outside of the vehicle, they must also be thermally controlled or in operation continuously. There could be a pump on the vehicle side which circulates the water.

7.3.3 Thermal Heat Sync

The presence of an exposed metal plate on the suit upper torso constitutes a heat sink. Thermal analysis is necessary to characterize the impact of the SIP acting as a conductor to the spacecraft and its effects on adjacent suit components such as batteries. An examination into SIP materials could be done to alleviate this issue along with thermal control (passive and command controlled) of the suitport interface on the vehicle. Covers may need to be developed keeping the thermal heat sink in consideration.

7.3.4 Environmental Protection

The vehicle cabana or environmental cover is undefined at this point. The amount of environmental protection from dust, micrometeoroid debris, Ultra Violet (UV) and ionizing radiation, and thermal environments are assumed to be mostly provided by the vehicle.

7.3.5 100% O2

Space Suits inherently have some amount of leakage. The suitport vestibule volume is small and suit leakage will enrich the vestibule environment during storage meaning that at startup, the external surfaces of the PLSS may be exposed to oxygen enriched environments of 100% O2. Additionally, if an off-nominal leak develops inside the PLSS during an EVA, resulting in an EVA terminate or abort, a suitport ingress scenario would result in the PLSS being exposed to an elevated oxygen environment at the conclusion of the EVA. Therefore, the PLSS must be designed to operate with not only 100% O2 inside the vent loop but also with 100% O2 on all surfaces which would nominally be exposed to the cabin environment.

7.3.6 Don/Doff

2012 and 2013 suitport testing showed difficulties during pressurized don/doff for several different reasons already mentioned in this document. Reference CTSD-

ADV-1014 Z-1 Suit and Pneumatic Flipper Suitport Chamber B Test Report for findings and suggestions for further ground testing and reduced gravity testing.

7.3.7 PGS Impacts and Suit Center of Gravity

The integration of the SIP with the suit causes the CG to move up (Y direction) and back (Z direction), potentially complicating ambulatory capability. Additional hardware, resulting from suitport compatibility will contribute to increasing suit on-back mass. Tests and evaluations should be performed to assess the impacts and determine if the vehicle can decrease these impacts.

7.3.8 PLSS Impacts

Impacts to the PLSS include additional on-back mass (vacuum plumbing for the regulators, beefier pumps, etc.), PLSS outer mold line, environmental exposure, and suit center of gravity as listed above. Assessment should be performed to determine what the vehicle can do to decrease these impacts.

8.0 SUMMARY

The EVA community is seeking innovative solutions to the challenge of transferring a pressurized suited crewmember from within the spacecraft to an external environment and back. It is desired to find airlock solutions that make progress towards:

- Improved consumables usage
- Increased crew autonomy
- Increased quantity and access of EVAs
- Reduced prebreathe time
- Mitigation of dust intrusion
- Provision for a layered defense for planetary protection

However, while addressing these challenges the solution should also consider features that improve overall EVA architecture such as:

- Providing unassisted don/doff
- Providing suit consumables recharge
- Providing the volume for donning/doffing and prebreathe
- Providing the volume for in-flight suit maintenance

This document surveys historical and currently suggested methods of solving these issues either in whole or in part. However, the remaining challenges associated with each known concept requires crossing the boundary between the EVA System and the host spacecraft. Gaining the perspective of a vehicle provider can allow further understanding of impacts to the suit as well as overall mission capabilities through the intermediary interface of the airlock.

Given the large number of interrelated variables associated with airlock design and operation, it can be easy to lose one's way when considering the merits of various conceptual solutions. This review was created to organize the conversation and mark the intellectual progress of the strategic planning community and EVA. Ultimately, this document intends to capture all of the constraints, highlight known open trades, and provide organization and citation of the most influential references useful to advancing ingress/egress methods, design strategies, and architectures.

Barring a revolution in propulsion technology, mass and volume will ultimately end up being the principal figures of merit for human spaceflight beyond LEO, once all other unique functional requirements are satisfied. Therefore, all trades must emphasize estimating these values in order to provide a useful comparison to contemporary and heritage solutions. Rigorously estimating mass and volume across the entire spaceflight architecture a given airlock solution will be used on allows it to be compared to heritage solutions. As proposed concepts are traded and taken beyond the conceptual graphics level, the language of mass and volume will facilitate the spaceflight community's acceptance of design choices.

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APPENDIX A
ACRONYMS AND ABBREVIATIONS

AES	Advanced Exploration Systems
AIA	Advanced Inflatable Airlock
A/L	Airlock
AEMU	Advanced Extravehicular Mobility Unit
ALCLR	Airlock Cooling Loop Recovery Unit??
ARCM	Asteroid Rendezvous Crewed Mission
ASPAT	Airlock Suitlock Suit Port Team
BCA	Battery Charger Assembly
BEAM	Bigelow Expandable Activity Module
BSA	Battery Stowage Assembly
CAD	Computer Aided Design
CCB	Configuration Control Board
CG	Center of Gravity
CO2	Carbon Dioxide
CR	Change Request
CSSS	Constellation Space Suit System
CTSD	Crew and Thermal Systems Division
CxP	Constellation Program
DCS	Decompression Sickness
DCIS	Dual-Chamber Hybrid Inflatable Suitlock
DCU	Display Control Unit
DDT&E	Design, Development, Test, and Evaluation
DOT	Destination Operations Team
DRATS	Desert Research and Technology Studies
DRM	Design Reference Mission
EA	JSC Engineering
EAM	Exploration Augmentation Module
EAWG	Exploration Atmosphere Working Group
ECLSS	Environmental Control and Life Support System
EDDA	EMU Don/Doff Assembly
EMC	Evolvable Mars Campaign
EMU	Extravehicular Mobility Unit
ESPO	EVA Systems Project Office
EV	Extravehicular
EVA	Extravehicular Activity
FCT	Future Capabilities Team
FGB	Functional Cargo Block
FOM	Figures of Merit
FPU	Fluid Pump Unit
FY	Fiscal Year

g	gravity
GER	Global Exploration Roadmap
HAT	Human Spaceflight Architecture Team
HEOMD	Human Exploration and Operations Mission Directorate
HHP	Human Health and Performance
HRP	Human Research Program
HUT	Hard Upper Torso
IDA	International Docking Assembly
INFO	Infomatics
IP	International Partner
IRD	Interface Requirements Document
IRMA	Integrated Risk Management Application
ISECG	International Space Exploration Coordination Group
ISLE	In Suit Light Exercise
ISRU	In-Situ Resource Utilization
ISS	International Space Station
IV	Intravehicular
IVA	Intravehicular Activity
JENOM	Joint EVA NBL Orion Mockup
LADTAG	Lunar Atmosphere Dust Toxicity Assessment Group
LCVG	Liquid Cooling Ventilation Garment
LDRO	Lunar Distant Retrograde Orbit
LEIA	Lightweight External Inflatable Airlock
LEO	Low Earth Orbit
MAG	Maximum Absorbent Garments
MASH	Minimalistic Advanced Soft Hatch
MAV	Mars Ascent Vehicle
MLI	Multi-Layer Insulation
MMD	Micrometeroid Debris
MMSEV	Multi-Mission Space Exploration Vehicles
MWS	Mini-workstation
MMWS	Modular Mini-Workstation
MTV	Mars Transit Vehicle
NASA	National Aeronautics and Space Administration
NBL	Neutral Buoyancy Lab
NDS	NASA Docking System
O2	Oxygen
OFV	On-orbit Fit Verification
OPR	Office of Primary Responsibility
ORU	On-Orbit Replaceable Unit
PLSS	Portable Life Support System
PPE	Personal Protective Equipment
PSA	Power Supply Assembly
psi	pounds per square inch

psia	pounds per square inch absolute
psid	pounds per square inch delta
PWR	Payload Water Reservoir
RAC	Requirement Analysis Cycle
R&R	Remove and Replace
REM	Rapid EVA Methods
RS	Russian Segment
SAFER	Simplified Aid for EVA Rescue
SMT	System Maturation Team
SIP	Suitport Interface Plate
SoA	State of the Art
SLS	Space Launch System
SPR	Small Pressurized Rover
SPCE	Servicing, Performance, and Checkout Equipment
SPTM	Suitport Transfer Module
SSPCB	Space Station Program Control Board
SSRMS	Space Station Remote Manipulator System
TBD	To Be Determined
TDS	Task Description Sheet
TRL	Technology Readiness Level
UIA	Umbilical Interface Assembly
USSR	Union of Soviet Socialist Republics
UV	Ultra Violet
VIIP	Visual Impairment / Intracranial Pressure
xEMU	Exploration Extravehicular Mobility Unit

APPENDIX B
SUITPORT TESTING OPTIONS

After the Near Term DRM Quick Study was performed, the team focused on coming up with a draft set of suitport testing options for the ground (B1.0) and on-orbit (B2.0):

- B1.0 Ground Testing Thermal vacuum Suit testing
  - Suit leakage (amount of leakage)
  - SIP seal leakage
  - Impact of leak rates into vestibule
- 0.9 psid analysis (Analysis is needed for suit leakage as well as thermal)
- SIP Stiffness
- Umbilical design for Vacuum access in a contingency case
- Suit Don/Doff
  - Difficulty for comparison to microgravity
  - Tightening gloves & boots after donning
- Radiation, Thermal (cabana assumptions for protection) analyses
- SIP Canted Dimensions (needed for vehicle bulkhead design – is this included in SIP Outer Dimensions?)
- SIP Surface Finish (sealing & Thermal & regolith mitigation & abrasion resistance)
- Vehicle vestibule equalization
- Ingress/egress controls and location (interior and exterior)
- 8.2 psid mobility (suitport operations, hatch latch, operation switches and controls, mate/demate umbilicals)
- Hardware suit to vehicle restraints/equipment for nominal testing
  - Minimizing flail
  - For ingress/egress from suit
- Suitport Random Vibration and Dynamic Loads
  - Hardware and suit restraints/equipment for vibration testing
- Suit/Tether attachment
- Dust mitigation and dust testing with simulants (dust into vehicle)
- Volume studies
  - Suit Maintenance capability
    - Nominal suit maintenance in rear-entry airlock
    - Contingency suit maintenance in pressurized rover cabin
- Prebreathe protocol
- Need hardware and materials testing for flammability
  - In cabin and in rear-entry airlock/cabana volume
    - Amount of suit leakage into cabana volume when used as suitport can build up
- ECLSS and thermal testing

- Failure scenarios
  - Incapacitated crewmember through suitport
- Post operations analyses of systems for suit and vehicle (corrosion, build-up, mechanical wear, chemical wear, etc.)

B2.0 CAPABILITIES TO TEST ON-ORBIT

- Validate activities that were previously demonstrated on the ground prior to flight
- Test end to end operations of Suitport
  - Insert ops con including performing EVAs
- Test end to end operations of Rear-Entry Airlock
  - Insert ops con including performing EVAs
- Initial case: unstow suit, attach to suitport shirtsleeve for first time
- Ingress/egress controls and location (interior and exterior)
- Don/doff in microgravity (based on feasibility testing)
- 8.2 psid mobility (hatch latch, operation switches and controls, mate/demate umbilicals)
- Intermodule integration (pressurize control and partial pressure control, reclamation air kept on module or in an accumulator for absolute pressure control?)
  - ISS or other module
- Hatch (vestibule) within Hatch (internal hatch) or Internal Hatch between two suitport hatches or crawl through suitport hatch
- Hypoxia/VIIP
- Met Rate
- Prebreathe protocol validation
- Dust Mitigation (using simulant? At LDRO?) and mud room
- Suit Maintenance capability (suit checkout, suit recharge, wipe-down, ORU R&Rs)
- Hardware suit to vehicle restraints/equipment for nominal testing
  - Minimizing flail
  - For ingress/egress from suit
- Translation aids for ingress/egress
- Translation aids, tethering, etc. compatible with ISS
- Suit/Tether locations
- Tools stowage/attachment to suit
- Porch and cabana ops
- Alignment for suit to suitport
- Failure scenarios
  - Emergency ingress via suitport
  - Emergency ingress via rear-entry airlock
  - Emergency ingress with incapacitated crewmember through suitport

    - Suit Restraints to facilitate pulling crewmember through suitport
  - Emergency ingress with incapacitated crewmember via internal hatch or hatch within a hatch (assuming suitport ops); do we need internal umbilicals and panels for this? Crew lock on ISS does not have it.
  - Emergency ingress with incapacitated crewmember through the rear-entry airlock
- Post operations analyses of systems for suit and vehicle (corrosion, build-up, mechanical wear, chemical wear, etc.)

APPENDIX C
CONCEPTUAL SUITPORT INTERFACE DESCRIPTION

C1.0 DRAFT CONCEPTUAL SUITPORT INTERFACE DESCRIPTION

The following lists the initial interface description set from both the suit perspective and the vehicle perspective.

C1.1 Space Suit

Microgravity Mobility with SIP Installed

Space suits should allow suited subjects within the anthropometric ranges to perform repeated circuits of the functional tasks shown in the Simulated Micro-g Functional Tasks Table without assistance in a simulated microgravity environment at EVA suit pressure. **[EX-1026]**

Rationale: All tasks will be performed with the SIP, a cover layer and display and control module (or volumetric mock-up thereof) installed.

TABLE C-1 SIMULATED MICRO-G FUNTIONAL TASKS AT EVA PRESSURE

Task Name	Description of Tasks to be Performed with Suit Pressurized to EVA Pressure
Visor Reach	Controlled operation of sun visor open/close. Perform two complete cycles.
Shoulder Touch	While standing, touch fingers of right hand to outside of left shoulder; hold for 5 sec. While standing, touch fingers of the left hand to outside of right shoulder; hold for 5 sec.
Wide Reach Translation	Demonstrate translation or slider bar that pushes laterally for 24 in. left and 24 in. right.
Hand-Over-Hand Translation	Demonstrate translation or pull loaded rope through ceiling mounted pulley.
Foot Restraint Ingress/Egress	Ingress and Egress the foot restraints
Pistol Grip Tool (PGT) Retrieve and Stow	Using body restraint tether mounted to square boss, stow PGT mock-up, rotate PGT/BRT combo to side and behind body, rotate PGT/BRT back to front, unstow PGT
Tether Point Reach	Using large-small retractable tether, place large hook on waist tether point, connect small tether hook to each other tether point (in series)
Small Object Transfer	Controlled motion to relocate object (minimum size 8” cube) from knee height on right side of body to knee height on left side of body with feet in a fixed position in the Articulating Portable Foot Restraint (APFR).

1-g Mobility with SIP Installed

Space suits should allow suited subjects within the anthropometric ranges to perform repeated circuits of the functional tasks shown in the 1-g Functional Tasks Table without assistance in a 1-g ambient environment at EVA pressure suit pressure. **[EX-1027]**

Rationale: All tasks will be performed with the SIP, a cover layer and display and control module (or volumetric mock-up thereof) installed.

TABLE C-2 1-G FUNTIONAL TASKS AT EVA PRESSURE

Task	Success Criteria
Single knee/single hand object pick-up	Controlled motion to kneel, lift 1.0lb object (minimum size 3”x2”x4”) with one-hand, controlled motion to standing while maintaining hold of object
Single knee/two hand object pick-up	Controlled motion to kneel, lift 2.0lb object (minimum size 8” cube) with two hands, controlled motion to standing while maintaining hold of object
Standing Toe Touch	Controlled motion down, touch fingers to top of each boot and rotate adjustment device, if present (may touch boot with hand of choice), controlled motion back to standing
Cross-body Reach	While standing, grasp handle (or 1.0lb object) from approximate subject eye-height with two hands on subject’s left side, controlled motion to bring handle/object to subject’s knee height on right hand side at a distance of 1 foot to the right of the subject, controlled return to start position.
Single hand object floor to shelf	Controlled lean to side, grab small suitcase (with a mass of 4 lbs and a volume of 4” x 6” x 8”) with one hand, keeping object in same hand place on shelf at subject eye-height on opposite side of the body without taking a step, return to start position. Repeat for both sides of the body.
Walking	Walk 20ft across level floor with stride length no less than 20% of unsuited subject stride length while walking
Visor Reach	Controlled two-handed operation of sun visor open/close. Perform two complete cycles.

DCS Treatment Pressure Mobility with SIP Installed

Space suits should allow suited subjects within the anthropometric ranges to perform repeated circuits of the functional tasks shown in the Functional Tasks

DCS Treatment Pressure Table without assistance in a 1-g ambient environment at DCS Treatment suit pressure. **[EX-1025]**

Rationale: All tasks will be performed with the SIP, a cover layer and display and control module (or volumetric mock-up thereof) installed.

TABLE C-3 1-G FUNTIONAL TASKS AT DCS TREATMENT PRESSURE

Task Name	Description of Tasks to be Performed with Suit Pressurized to DCS Treatment Pressure
Operate Switches and Controls	Demonstrate operation of all switches and controls
Mate & Demate Umbilical	Mate and Demate the Umbilical
Suit Hatch Operation	Cycle the rear hatch controls which includes: close, lock, unlock, and open twice using either hand while attached to a suitport simulator

Suitport

Space suits should be compatible with the operations outlined in EVA-EXP-0042, Exploration EVA SystemConcept of Operations Document. **[EX-1008]**

Rationale: This is an interface need for exploration with a suitport compatible vehicle. Contractor will provide the SIP as part of the design.

PLSS Ports

Space suits should be packaged so that vacuum access port(s), O2 recharge port, electrical connection, cooling water inlet and cooling water return are on the forward facing PLSS surface. **[EX-1028]**

Rationale: To ensure future Suitport compatibility, services which must be routed through the umbilical must face the front of the PLSS.

SIP Interface

Space suits should interface with a Suitport Interface Plate (SIP). **[EX-1029]**

Rationale: The suit to SIP interface is intended to be developed by the contractor and provided as a part of the RIDable content at PDR. The interface is expected to be both physical and structural. At a minimum the SIP will be supporting the weight of a 250 lb crewmember, the weight of the suit, and the plug load of a vehicle which is pressurized to 8.2 psi. The SIP is considered to be an internal interface to the space suit.

Operating in O2 Environment

Space suits should operate in a 100% O2 environment at 8.2 psia. **[EX-1014]**

Rationale: Space Suits inherently have some amount of leakage. The suitport vestibule volume is small and suit leakage will enrich the vestibule environment during storage meaning that at startup, the external surfaces of the PLSS may be exposed to oxygen enriched environments of 100% O2. Additionally, if an off nominal leak develops inside the PLSS during an EVA, resulting in an EVA terminate or abort, a suitport ingress scenario would result in the PLSS being exposed to an elevated oxygen environment at the conclusion of the EVA. Therefore, the PLSS must be designed to operate with not only 100% O2 inside the vent loop but also with 100% O2 on all surfaces which would nominally be exposed to the cabin environment.

Pressurized Suitport Donning

Space suits should be donnable by an unassisted crewmember while mounted to a suitport and pressurized to 8.4 psid (maximum). **[EX-1017]**

Rationale: This is required to support utilization of a Suitport on Exploration Class Vehicles with a cabin environment of 8.2 psi / 34% O2. During donning the interior of the suit will be exposed to the vehicle cabin pressure and the exterior will be at vacuum. For the purposes of this rationale donning starts with the occupant in IVA clothing and is considered to be complete when the hatch is closed and all suit functions necessary to establish pressure integrity have been completed.

Pressurized Suitport Doffing

Space suits should be doffable by an unassisted crewmember while mounted to a suitport and pressurized to 8.4 psid (maximum). **[EX-1018]**

Rationale: This is required to support utilization of a Suitport on Exploration Class Vehicles with a cabin environment of 8.2 psi / 34% O2. During doffing the interior of the suit will need be equalized to the vehicle cabin pressure and the exterior will be at vacuum. For the purposes of this rationale, doffing starts with the suit docked to the suitport and the hatch closed. Doffing is considered to be complete when the occupant has completely egressed the suit and all hardware worn by the occupant is physically detached.

Suitport Hatch Clearance

Space suits should contain adequate cable/line length for all hardware which crosses the suit hatch parting line to allow it to rotate open while translating a minimum of 4 inches. **[EX-1019]**

Rationale: This is required to support utilization of a Suitport on Exploration Class Vehicles. Interfacing with past prototype exploration vehicles indicates that the hatch will not only have to rotate open but will also have to translate a minimum of 4 inches to clear the vehicle bulkhead and nearby hardware.

C1.2 Space Suit Interfaces

Suitport SIP Proximity Sensors

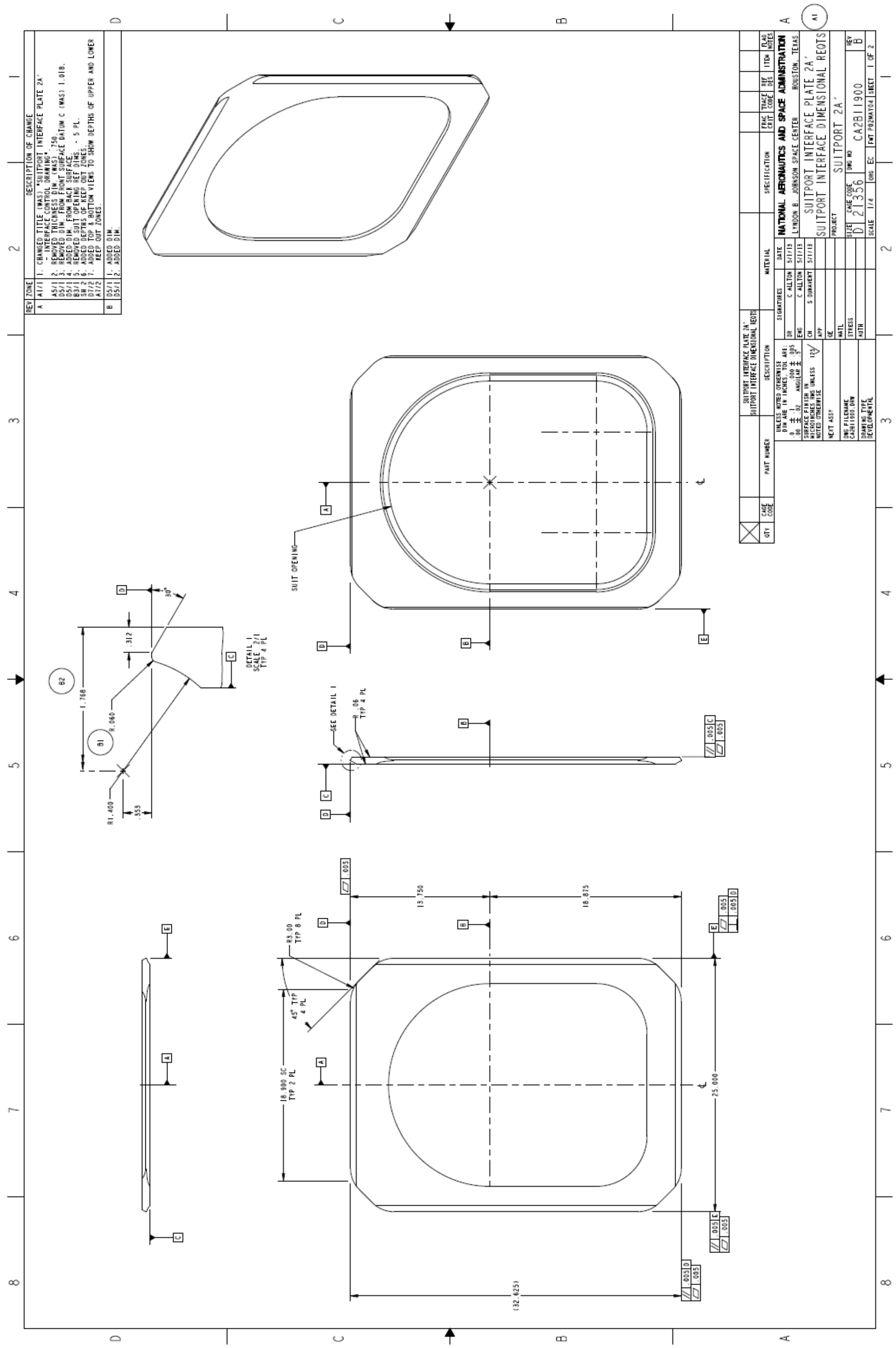
Space suits should contain proximity sensors at the corners of the SIP. **[EX-1020]**

Rationale: This is required to support utilization of a Suitport on Exploration Class Vehicles. In the current suitport concepts, the proximity sensors are utilized to allow the vehicle to sense when the suit is fully engaged in the Suitport.

Suitport Interface Plate Dimensions

Space suits should employ the use of a Suitport Interface Plate (SIP) that implements the features and keep out zones defined on drawing number CA2B11900 rev B in SIP Dimensions Figure. **[EX-1021]**

Rationale: The geometry of the SIP must be defined to ensure a working interface with the suitport. Note that the 0.005 flatness spec in drawing CA2B11900 Rev B is only required in the keep-out zone areas, and elsewhere a flatness of 0.065 is allowed.



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
SUITPORT INTERFACE PLATE 2A'
SUITPORT INTERFACE DIMENSIONAL REQTS
SUITPORT 2A'
21356
CA2B11900
SUIT OPENING
13.750
18.875
25.000
(32.625)

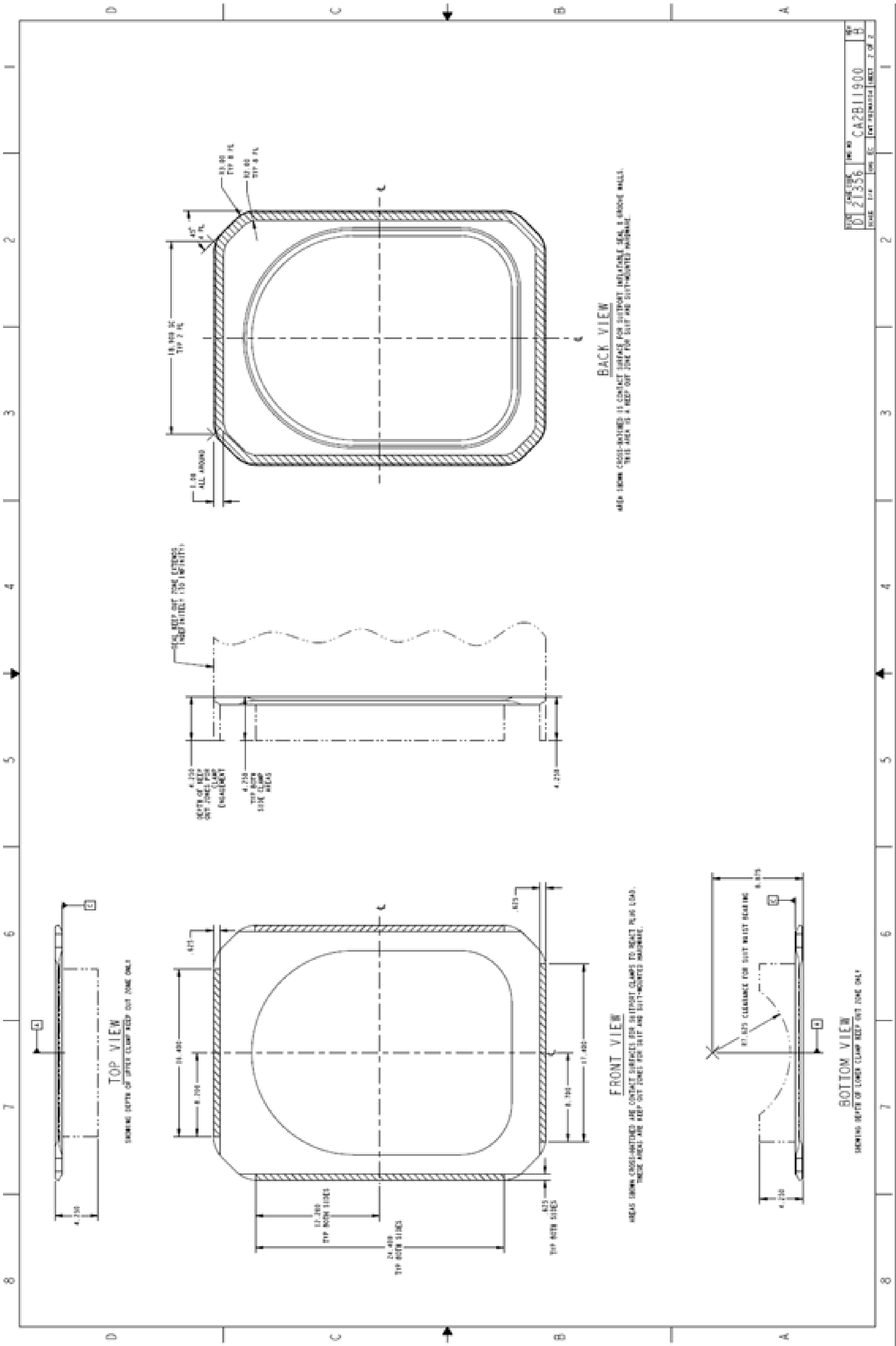


FIGURE C-4 SIP DIMENSIONS

Suitport Interface Plate Differential Deflection

Space suits should have a SIP to suitport sealing interface differential deflection of less than 0.020 inches when integrated with the suitport and pressurized to a maximum of 8.4 psid. **[EX-1022]**

Rationale: Various loads are induced by the suitport, suit, PLSS, and crewmember that could impair an optimal SIP/suitport interface or suit function. SIP flatness, for example, must be maintained to ensure an adequate seal and function of suitport and hatch locking mechanisms. This, in conjunction with maintaining proper hatch latch function at 8.4 psid, may drive aspects of the SIP, hatch, or hatch locking mechanism design such as thickness and material selection, among others.

C1.3 Vehicle Interfaces

EVA Suit Protection on Suitport

The vehicle will provide protection (TBD) for suits stowed external to the vehicle. **[VI-1029]**

Rationale: Suits stowed externally to the vehicle, e.g., Suitport, will be exposed to the EVA environment for periods of time far in excess of 624 hours. Protection from the thermal, ionizing, and non-ionizing environment will contribute significantly to the life of the suit. Resolution of the environmental protection (TBD) will provide the degree of protection afforded.

C2.0 FORWARD WORK ITEMS

The table Forward Work Items lists the specific items in the document that are not yet known, need to be discussed, or added to the document.

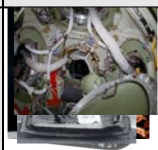
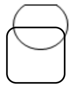
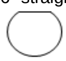
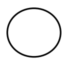
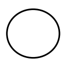
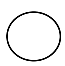
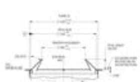
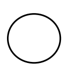
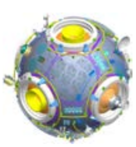
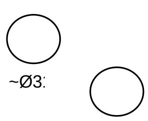
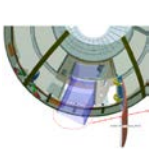
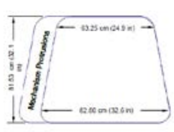
TABLE C2-1 FORWARD WORK ITEMS

Item	Section	Description
Reference Documents		Documents or studies referred to in the document need to be listed at the front of this document.
Suitport Ops Con		Update operational concepts in EVA-REF-004, Exploration EVA Capabilities and Operational Concepts Document.
Additional Suit Related Interfaces		Forward work could include the following: Umbilical design for Vacuum access in a contingency case

		Tightening gloves & boots after donning Leakage (SIP to suit) SIP Mass support of crew and suit weight SIP thermal insulation from rest of suit SIP seal at suit/SIP interface SIP hatch lock/unlock mechanism operation
Additional Suitport Interfaces		Forward work could include the following: Radiation, Thermal (cabana assumptions for protection) SIP Canted Dimensions (needed for vehicle bulkhead design – is this included in SIP Outer Dimensions?) SIP Surface Finish (sealing & Thermal & regolith mitigation & abrasion resistance) Dust into the vehicle Vehicle vestibule equalization Suitport Random Vibration and Dynamic Loads SIP seal leakage Long Duration Pressurized Materials Creep
Particulate Control in Suitport, Planetary Protection, Crew Health, and Sample Contamination		Dust infiltration/contaminant control/cleaning techniques/venting. Space suits should limit the concentration in the suitport vestibule atmosphere of particulate matter ranging from 0.5 μm to 10 μm (respirable fraction) in aerodynamic diameter to <1 mg/m3 and 10 μm to 100 μm to <3 mg/m3. Rationale: Inhalation of particulates can cause irritation of the respiratory system. Limits for particulates are based on Occupational Safety and Health Administration (OSHA) standards for nuisance dusts, which is the best analog for the ordinary dust present in spacecraft. This does not include reactive dust (e.g., LiOH). Reference CCT-REQ-1130 ISS Crew Transportation and Services Requirements Document Revision A.

APPENDIX D
HATCH AND AIRLOCK HISTORY

Vehicle; Yrs of service	Visual	Shape	# of Hatches	Dimensions	Type of EVA Life Support	Source
Voskhod 2 Volga Airlock (USSR); 1965		~Ø26" (only used once then disposed)	2 small hatches	EVA hatch: 26 in diameter	Umbilical; TBD open or closed loop	See Appendix C of EVA-EXP-0031
Gemini (USA); 1962-1966		~15" ~51.0" ~37"	2 (Docking and EVA)	EVA hatch: 1ft 3 in deep x 4ft 3 in long x 3 ft 1 in wide	Umbilical; closed loop, unganged	See Appendix C of EVA-EXP-0031
Apollo Crew Module (USA); 1963-1972		~23.2" ~29.0" ~34.0"	2 (Docking and EVA)	EVA Unified Hatch @ 23.2 in x 29 in x 34 in	Umbilical; open loop, unganged	See Appendix C of EVA-EXP-0031
Apollo Lunar Module (USA); 1969-1972		32.0" 32.0"	2 (Docking and EVA)	EVA hatch: 32 in square	PLSS	See Appendix C of EVA-EXP-0031
Skylab A/L - used Gemini hatch (USA); 1973-1974		~15" ~51.0" ~37"	2 (Docking and EVA)	EVA hatch: 1ft 3 in deep x 4ft 3 in long x 3 ft 1 in wide	Umbilical; open loop	See Appendix C of EVA-EXP-0031
Shuttle A/L (USA); 1983-2011		36" straight Ø40" diameter	2 EVA hatches	40 in diameter, (one flat side minimum dimension of 36 in)	PLSS	See Appendix C of EVA-EXP-0031
Mir – Transfer Compartment Node Module (USSR/RS) 1986-2001		~Ø31.5"	5 Docking/ Berthing Ports (Prior to Kvant 2, no EVA hatches, but they could egress through any of the 5 ports)	TBD Assuming hatch is similar to Docking hatches: 31.49 in (800 mm)	PLSS	See Appendix C of EVA-EXP-0031
Mir Airlock – Kvant 2 (USSR/RS) 1989-2001		~Ø39"	2+	EVA hatch: 39.37 in (1m)	PLSS	See Appendix C of EVA-EXP-0031

Vehicle; Yrs of service	Visual	Shape	# of Hatches	Dimensions	Type of EVA Life Support	Source
ISS CBM (USA) 1998-present			Common Berthing Mechanism hatches (many)	50 in x 50 in	None	SSP 41004 Part 1 Rev H
ISS USOS Quest A/L (USA) 2001-present		36” straight  Ø40” diameter	1 Nominal EVA hatch; 1 Contingency EVA hatch	Nominal EVA Hatch: 40 in diameter, (one flat side minimum dimension of 36 in)	PLSS	See Appendix C of EVA-EXP-0031
ISS RSOS Docking Compartment DC1 - Pirs (RS) 2001-~2017			4	2 EVA hatches: 39.47 in (1m) Docking hatch: 31.49 in (800 mm) Module hatch: 43.3 in (1100mm)	PLSS	See Appendix C of EVA-EXP-0031
ISS RSOS Zvezda Transfer Compartment (RS) 2001-present			3	To Functional Cargo Block (FGB): 31.49 in (800mm) To Pirs: 43.3 in (1100mm) To Poisk: 43.3 in (1100mm)	Contingency Only	See Appendix C of EVA-EXP-0031
ISS RSOS MRM2 - Poisk (RS) 2009-present			4	2 EVA hatches: 39.47 in (1m) Docking hatch: 31.49 in (800 mm) Module hatch: 43.3 in (1100mm)	PLSS	See Appendix C of EVA-EXP-0031
Orion and TBD NDS/IDA Docking hatches			1 Docking	Docking hatches: 31.49 in (800 mm) transfer passageway inside petals	None planned as of 2015; future ops may change	IDSS (International Docking System Standard) IDD Rev D Final 043015
Node Module UM (Docking Ball) - (RS)			6 (5 module hatches and 1 vehicle hatch)	5 module hatches: 43.3 in (1100mm) 1 vehicle hatch: 31.49 in (800 mm), Nadir position	None planned as of 2015; future ops may change	TBD
Orion Side Hatch (USA)			1 (possible contingency EVA)	24.9 in x 32.1 in height x 32.6 in	None planned as of 2015; future ops may change	MPCV 72000 SRD Rev C

National Aeronautics and Space Administration
NASA
Historical Airlock and EVA Hatches
September 17, 2015

Extravehicular Activity Management Office

Outline

- **Vehicle Structure/Modules (Airlocks)**
  - Voskhod
  - Gemini Capsule
  - Apollo Lunar Module
  - Skylab
  - Shuttle
  - MIR
  - ISS Airlock
  - ISS Russian Airlocks
  - Orion
  - NASA Docking System (NDA)/International Docking Adapter
- **System Consumables Reference**
  - Voskhod
  - Gemini Capsule
  - Apollo Lunar Module
  - Skylab
  - Shuttle
  - MIR
  - ISS Airlock
  - ISS Russian Airlocks
  - Orion
  - NDS/IDA
- **Airlock Structure/Consumables Comparison**

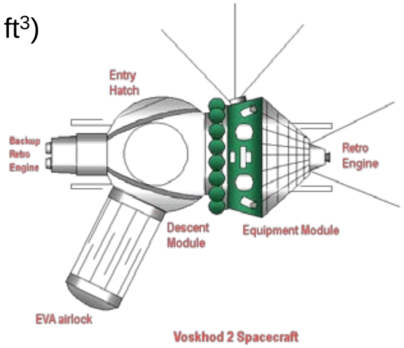
Extravehicular Activity Management Office

Voskhod

- **Voskhod Airlock (1965)**
  - Inflatable airlock (24 min tethered spacewalk; airlock jettisoned after use)
  - 1st EVA in history, by Alexei Leonov (only EVA)
  - Double-walled fabric airlock tube (name – Volga)
    - Length: 2.50 m (8.2 ft)
    - 1.2 m (3.9 ft) wide metal upper ring that fit over Voskhod's inward-opening airlock hatch 65 cm (26 in) wide
    - Inward opening EVA hatch
  - Internal volume 2.50 m^3 (88 ft^3)

Image from museum

Alexi Leonov first EVA on 3/18/65
NASA

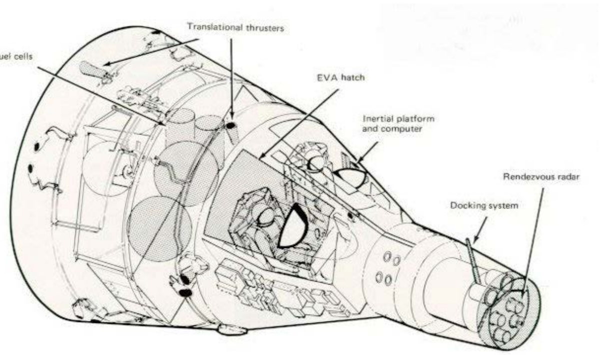


Source/References:
1. NASA RP 1357 Mir Hardware Heritage
2. Walking to Olympus: An EVA Chronology

Extravehicular Activity Management Office

Gemini Capsule

- **Gemini Capsule – (comprised of three modules: reentry, retro, and equipment)**
  - Enlargement of the Mercury capsule
  - Length: 5.8 m (19 ft)
  - Diameter: 3 m (10 ft)
  - Weight: 3851 kg (8490 lb)
  - Habitable Volume: 2.55 m^3 (90 ft^3)
  - Two hatches (crew of 2) (outward opening hatch)
    - EVA hatch dimensions
      - 1ft 3 in deep x 4ft 3 in long x 3.1 ft 1 in wide



- **Reentry Module**
  - Length: 3.4 m
  - Maximum diameter: 2.3 m
  - Habitable Volume: 2.55 m^3 (90 ft^3)
  - Total Mass: 1982 kg (4370 lb)
- **Total EVAs performed**
  - 9 EVAs

EVA Hatch – from Gemini IV
http://airandspace.si.edu/collections/artifact.cfm?object=nasm_A19680035000

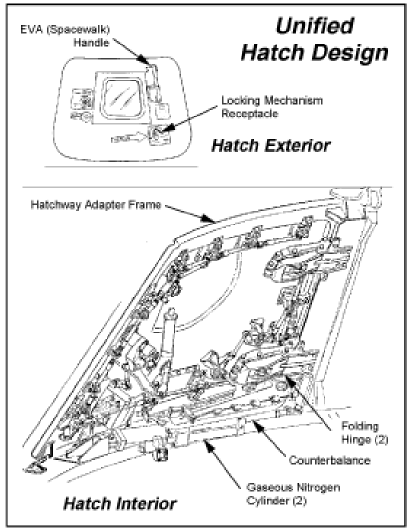
Ed White:
1st US EVA on 6/3/65, NASA

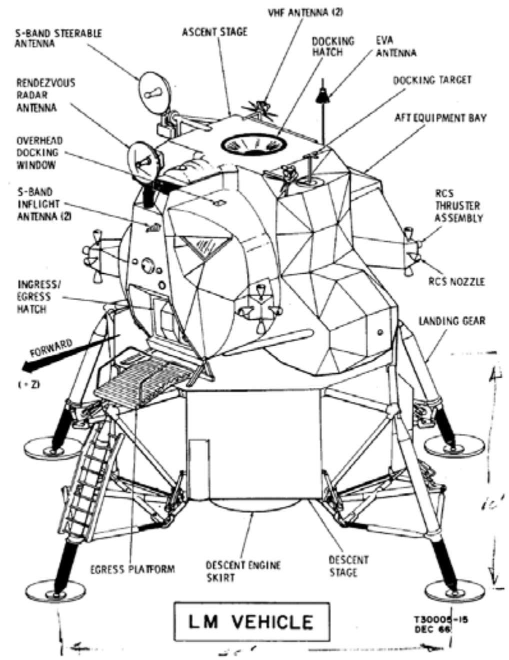
Sources/References:
1. http://science.ksc.nasa.gov/history/gemini/gemini-spacecraft.txt
2. http://www.nasa.gov/audience/forstudents/k-4/stories/what-was-gemini-program-k4_prt.htm
3. http://www.braeunig.us/space/specs/gemini.htm
4. Walking to Olympus: An EVA Chronology

Extravehicular Activity Management Office

Apollo Lunar Module

- **Dimensions**
  - Overall height: 7 m (22 ft 11 in), legs extended
  - Width: 9.4 m (31 ft), diagonally across extended landing gear
  - Maximum diameter: 4.3 m (14.1 ft)
  - Habitable volume: 4.5 m^3 (160 ft)
  - Crew compartment: 2.35 m diameter x 1.07m long
  - Total mass: 15,200 kg (33,510 lb) for H-series [16,440 kg (36,244 lb) for J-series], with crew and propellant
- **Ascent Stage**
  - Height: 3.76 m (12 ft 4 in)
  - Diameter: 4.29 m (14ft 1 in)
- **Descent Stage (unmanned portion)**
  - Height: 3.23 m (10 ft 7 in)
  - Diameter: 4.22 m (13 ft 10 in)





Sources/References:

1. SNA-8-D-027(III) Rev 2, CSM\LM Spacecraft Operational Data Book Volume III Mass Properties
2. NASA/TP-2010-216131: Worldwide Spacecraft Crew Hatch History
3. https://airandspace.si.edu/exhibitions/apollo-to-the-moon/online/apollo-11/about-the-spacecraft.cfm
4. http://www.braeunig.us/space/specs/lm.htm
5. Apollo News reference – Lunar Module Quick Reference Guide published by Grumman
6. http://www.hq.nasa.gov/office/pao/History/alsj/frame.html

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Apollo Lunar Module (cont.)

- **Flight History**
  - First flight: 22-Jan-1968; first manned flight 3-Mar-1969 (Apollo 9)
  - Last flight: 7-Dec-1972 (Apollo 17)
  - Number of manned flights: 9
  - Crew size: 2
  - Hatch: 32 in (square), required complete depress of cabin for EVA
- **Total EVAs performed**
  - 20 EVAs
    - On Lunar surface: 15
    - From Command Module: 5

Apollo 11 – Buzz Aldrin egress LM (AS11-40-5863), NASA http://spaceflight.nasa.gov/gallery/images/apollo/apollo11/html/as11-40-5863.html

Source/Reference:
1. http://www.nasa.gov/directorates/somd/reports/eva.html

Apollo 9 – David Scott egress CM (AS09-20-3064), NASA http://spaceflight.nasa.gov/gallery/images/apollo/apollo9/html/as09-20-3064.html

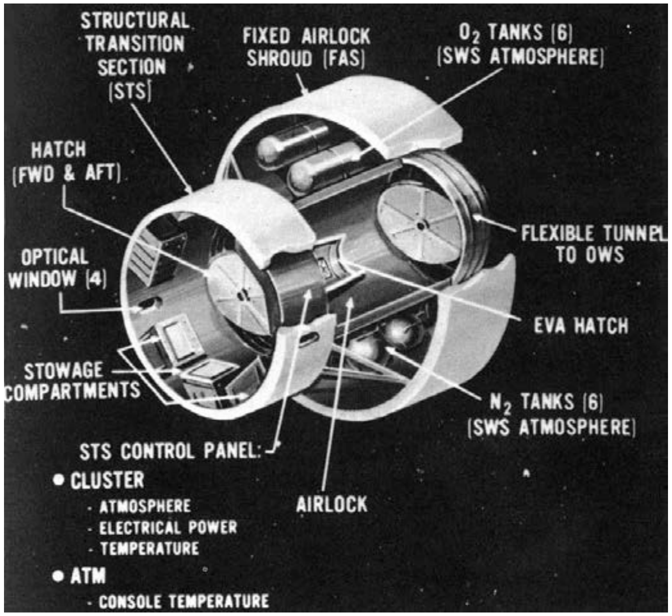
Extravehicular Activity Management Office

Skylab

- **Airlock Module (comprised of STS and radiators, Tunnel Assembly, Flexible Tunnel Extension, and Support Truss Assembly)**
  - Gross wt: 15,166 lb (launch weight)
  - Working volume: 610 ft^3
  - Overall length: 5.4 m (211.54 in)
  - Diameter: 3 m (10 ft)

- **Structural Transition Section (STS)**
  - Length: 47 in
  - Diameter: 120 in (provided transition from 120-in diameter to 65-in diameter to mate with tunnel assembly)
  - Enclosed volume: 288 ft^3

- **Tunnel Assembly**
  - Length: 153 in
    - Forward compartment -31 in (support for stowage containers, tape recorders, and misc. equipment)
    - Center (lock) compartment – 80 in (included a modified Gemini crew hatch for ingress/egress during EVA). Hatch was outward opening
    - Aft compartment – 42 in (housing to OWS environmental control system)
  - Diameter: 65 in
  - Volume: 322 ft^3
    - Center (lock) compartment – 170 ft^3



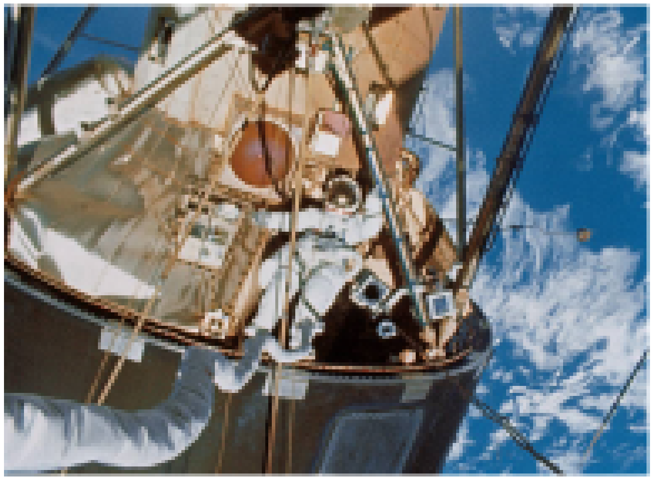
Skylab artist's concept illustrating cutaway view of Skylab Airlock Module: NASA

Sources/References:
1. MSFC Airlock Final Technical Report (MDC E0899 Volume 1/NASA TM X-64810)
2. SP-400 Skylab, Our First Space Station - http://history.nasa.gov/SP-400/contents.htm
3. http://www.astronautix.com/craft/skylab.htm
4. Walking to Olympus: An EVA Chronology

Extravehicular Activity Management Office

Skylab (cont.)

- **Flexible Tunnel extension**
  - Length: 13 in
  - Diameter: 42.5 in
- **Fixed Airlock Shroud (FAS)**
  - Gross wt: 22,749 lb (launch weight)
  - Length: 80 in
  - Diameter: 260 in
- **Deployment Assembly (DA)**
  - Gross wt: 3,744 lb (launch weight)
  - Length (upper): 122 in
  - Length (lower): 194 in
- **EVA Hatch:**
  - (see slide on Gemini for dimensions)



S74-17458:Ed Gibson exiting from Skylab hatch – final Skylab EVA on 2/3/74
http://www.spaceflight.nasa.gov/gallery/images/skylab/skylab4/html/s74-17456.html

	Calculated	Measured
Airlock Module	16,188 lb	16,937 lb
Deployment Assembly	4069 lb	4044 lb
Fixed Airlock Shroud	28,312 lb	28,408 lb
Total	49,269 lb	49,389 lb

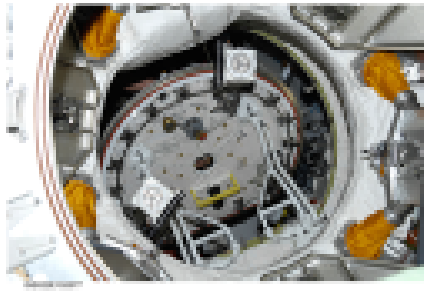
- **Launch weights**
  - Oxygen – 6085 lb
  - Nitrogen – 1624 lb
- **Total EVAs performed**
  - 10 EVAs

Source/Reference:
1. http://www.nasa.gov/directorates/somd/reports/eva.html

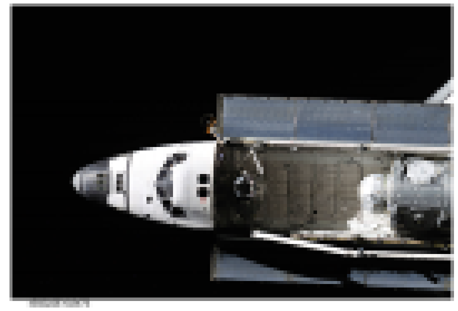
Extravehicular Activity Management Office

Shuttle

- **Shuttle Airlock**
  - Length: 210 cm (83 in)
  - Inside diameter of 160 cm (63 in)
  - Internal volume of 4.25 m^3 (150 ft^3); 375 kg when empty
  - Two hatches
    - EVA Hatch size: 40 in diameter, (one flat side minimum dimension of 36 in)
    - Inward opening hatch

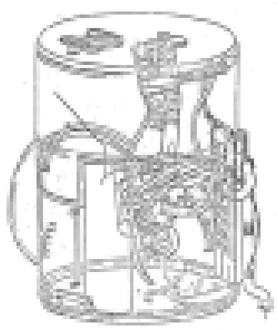


NASA ISS022E102577: Shuttle EVA Hatch, external view



NASA ISS022e102473: Shuttle airlock in payload bay

- **Total EVAs performed (non-ISS)**
  - 74 EVAs
    - (need to verify current accurate count)



NASA ISS011e11350: 2 Crew in Shuttle Discovery Airlock (NASA Imagery Online) STS-114

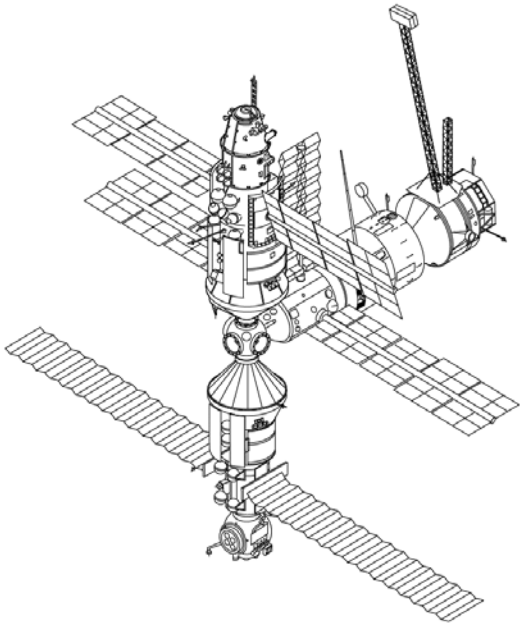
Sources/References:

1. http://www.spaceflight.nasa.gov/shuttle/reference/shutref/structure/airlock.html
2. http://www.nasa.gov/directorates/somd/reports/eva.html

Extravehicular Activity Management Office

MIR

- **EVA hatch was outward opening (for Kvant 2)**
- **Mir base block**
  - Gross Mass: 21,000 kg (46,000 lb)
  - Height: 13.13 m (43.07 ft)
  - Span: 29.73 m (97.53 ft) – solar arrays
  - Maximum diameter: 4.15 m
  - Habitable Volume: 90 m^3
- **Mir complex (Mir base block – Kvant, Kvant 2, and Kristall) with docked Soyuz-TM and Progress –M spacecraft (as of 11/15/94)**
  - Weight: 93, 649 kg (206,461 lb)
  - Length: 33m
  - Height: 13.13 m (43.07 ft)
  - Maximum diameter: 4.35 m (habitable modules)
  - Habitable Volume: 372 m^3



Sources/References:

1. NASA RP 1357 Mir Hardware Heritage
2. http://www.astronautix.com/craft/mir.htm

Extravehicular Activity Management Office

MIR (Cont.)

- **Mir Airlock – Kvant**
  - Weight: 9,600 kg
  - Length: 5.8 m
  - Maximum diameter: 4.15 m
  - Habitable volume: 40 m^3
- **Mir Airlock – Kvant 2 (top of stack)**
  - Launch weight – 19, 565 kg
  - Length: 13.73 m
  - Diameter: 4.35 m
  - Habitable volume: 61.3m^3
  - EVA Hatch size: 1m (39.37 in)
- **EVAs**
  - Total performed: 75
    - Outside Mir: 72
    - Inside Spektr Module (IVA): 3

Source/Reference:

1. http://www.nasa.gov/directorates/somd/reports/eva.html

- **Mir was gone by early 2001 as ISS was growing in orbit. Mir was deorbited on March 23, 2001.**

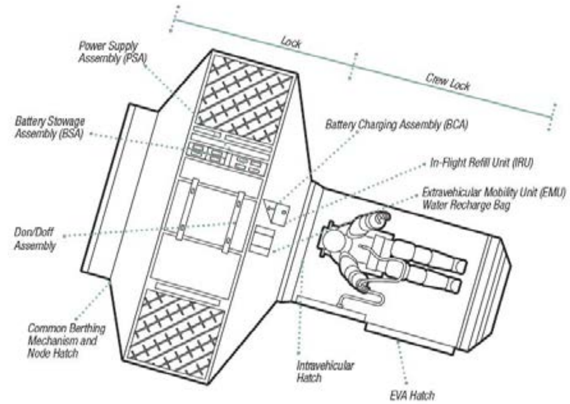
Mike Foale: Mir-23 & Mir 24 (5/97), view of Mir space station airlock including Orlan suits
http://spaceflight.nasa.gov/history/shuttle-mir/multimedia/m-photo.htm

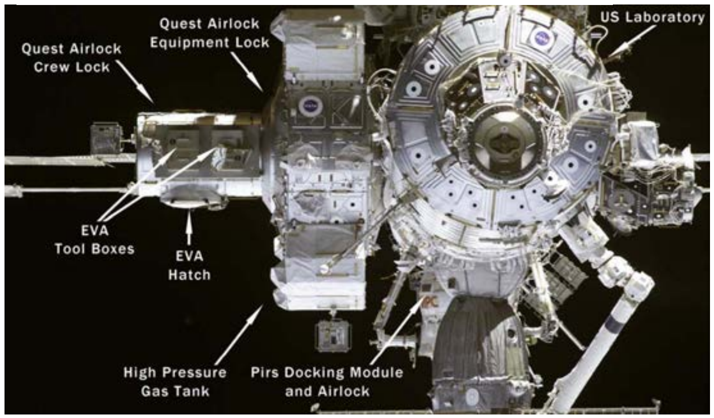
Linenger: Mir-22 & Mir 23 (1/97), exit hatch in Kvant-2 primary airlock
http://spaceflight.nasa.gov/history/shuttle-mir/multimedia/linenger-photos/linenger-p-008.htm

Extravehicular Activity Management Office

ISS Airlock

- **ISS Airlock**
  - Equipment lock stores spacesuits and equipment, the Crew Lock is depressed for ingress/egress (design based on Shuttle airlock)
  - Length: 5.5 m (18 ft)
  - Diameter: 4m (13.1 ft)
  - Volume – 34m^3
  - EVA Hatch size: 40 in diameter (one flat side minimum dimension of 36 in)
    - Inward opening EVA hatch
  - Total mass: 9932 kg (21,877 lb)
- **Total EVAs performed to construct/maintain ISS**
  - 188 EVAs (as of Expedition 44, 8/10/15)
    - From docked Space Shuttle: 28
    - From ISS Airlock: 112
    - Russian EVAs: 48





View from Shuttle Atlantis on STS-110, NASA

Sources/References:
1. https://www.nasa.gov/mission_pages/station/structure/elements/quest.html
2. http://www.nasa.gov/directorates/somd/reports/eva.html
3. Reference Guide to the International Space Station, Utilization Edition July 2015

Extravehicular Activity Management Office

ISS Airlock – cont.

NASA ISS033e018290: Crewlock

NASA ISS028e016328: Egress ISS Airlock

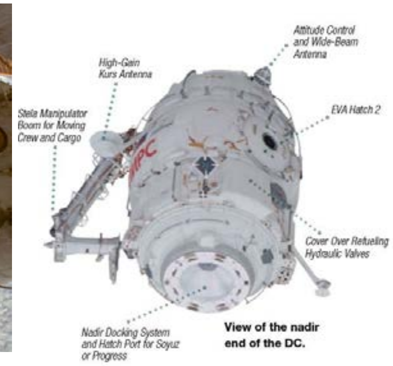
NASA JSC2013e007129:
1st egress from ISS Airlock

Extravehicular Activity Management Office

ISS Russian Airlocks

- **Russian Docking Compartment (DC) and Airlock Pirs (Pier)**
  - Provide the capability for EVA using Russian Orlan suits.
  - Provide contingency capability for ingress for US EMU EVAs.
  - It also has a docking system with a port for docking of Soyuz and Progress logistics vehicles.
  - Launched in and docked to ISS in 2001.
  - Plan is for it to be detached and jettisoned and replaced with a Russian Multi-Purpose Logistics Module (current timeline is 2017).

NASA ISS017e011287:
Pirs Airlock



View of the nadir end of the DC.

- **Pirs**
  - Length: 4.9 m (16 ft)
  - Maximum diameter: 2.55 m (8.4 ft)
  - Mass: 3,838 kg (8,461 lb)
  - Volume 13 m^3 (459 ft^3)
  - Two identical EVA hatches 1m (39.37 in) diameter – Inward opening EVA hatches

- **Total EVAs performed from Pirs (as of Expedition 44, 8/10/15)**
  - Total: 46

Sources/References:

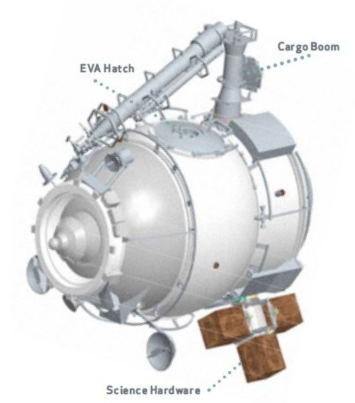
1. https://www.nasa.gov/externalflash/ISSRG/pdfs/russiandocking.pdf
2. http://www.nasa.gov/directorates/somd/reports/eva.html
3. Reference Guide to the International Space Station, Utilization Edition July 2015

NASA ISS009-E-17168:
Pirs Docking Compartment with Orlan Spacesuits

Extravehicular Activity Management Office

ISS Russian Airlocks

- **Russian Mini-Research Module (MRM) 2 and Airlock Poisk (Explore)**
  - Is almost identical to Pirs Docking Compartment
  - Additionally provides systems for servicing and refurbishing of the Orlan suits
  - Allows extra space for scientific experiments including power supply outlets and data transmission interfaces for two science payloads
  - Launched in 2009



Poisk Airlock

Source/References:
1. https://www.nasa.gov/externalflash/ISSRG/pdfs/MRM2.pdf
2. Reference Guide to the International Space Station, Utilization Edition July 2015

- **Poisk**
  - Length: 4.9 m (16 ft)
  - Maximum diameter: 2.55 m (8.4 ft)
  - Mass: 3,795 kg (8,367 lb)
  - Volume 14.8 m^3 (523 ft^3)
  - Two identical EVA hatches 1m (39.37 in) diameter – Inward opening EVA hatches

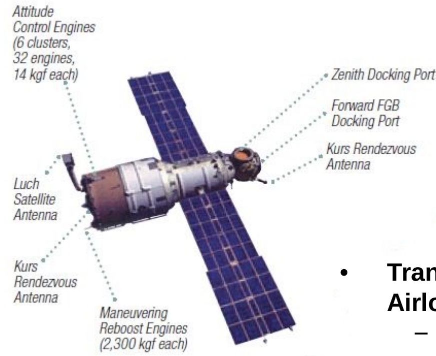
- **No EVAs have been performed out of Poisk**
  - Current plan is for Russian EVAs to be performed from Poisk once the Russian MPLM is integrated with ISS

Poisk Airlock: after arriving at ISS (November 2009)

Extravehicular Activity Management Office

ISS Russian Airlocks

- **Transfer Compartment**
  - Located on the forward port of the service module Zvezda (integrated with service module)
  - Serves as the location for docking to other modules/spacecraft
  - Used as an airlock for Russian EVAs (contingency)
- **Hatches (at the three docking ports) – inward opening**
  - To Functional Cargo Block (FGB): 1100mm (43.3 in)
  - To Pirs (1100mm) 43.3 in
  - To Poisk (1100mm) 43.3 in



Source/References:
1. Zvezda Press Kit, July 7, 2000
2. Reference Guide to the International Space Station, Utilization Edition July 2015

- **Transfer Compartment as Airlock**
  - Only EVA was 19 min on Expedition 2 (never left module)
  - Internal spacewalk prep for arrival of Poisk on Expedition 20

NASA ISS032e020830: Interior of Zvezda Transfer Compartment

NASA ISS020e007223: Zvezda Transfer Compartment with no airlocks attached

NASA ISS017e11097: Zvezda Transfer Compartment with Pirs airlock and Soyuz attached

Extravehicular Activity Management Office

Vehicle Consumables

- **The following slides address the question of "Per a single ISS EVA, what is the total consumables impact?"**
- **The methodology used to determine this is as follows:**
  - The following numbers are calculated per EMU, per EVA
  - Since ISS uses a 2-Crew for any US EVA as a rule, we would *double* these values in order to determine the total Program impact of a given EVA
  - These values are based upon Certification Specs and then compared to Actuals using JSC-MOD's On-Orbit Tracker (OOT) record of actual flight notes
    - The EVA Console team (JSC-CX) records EVA Consumable Actuals as a matter of course during pre-post EVA servicing events
    - These "Internal Notes" were mined from OOT by JSC-XX as a data reference
  - Though Loop Scrubs are typically Calendar Driven (due every 90 days) they must also be conducted within at least two weeks of a given EVA
    - Thus, for this data set, we assume that at least 1 Loop Scrub can be attributed to a given EVA *on average*.
    - It is known that in some cases it is higher, in some lower (depends on how regularly EVA's are being done which changes through time based upon the "health" of ISS and other operational variations such as External Payloads utilization.
    - This is a working assumption that is analytically inserted into the bottom line summary and could be easily changed in the calculations spreadsheet given superior rationale
  - Battery recharges include EMU Battery, REBA Battery, Helmet Light Battery, PGT Battery
    - It is known that the L-REBA battery displaces the need for stand-alone Helmet Light Batteries, but the total amount of energy used is the same

Extravehicular Activity Management Office

Vehicle Consumables

- **Per a single ISS EVA, what is the total consumables impact?"**
  - _58.25_ hrs. of Crew Time is required on average to prep the EVA System (pre EVA)
    - Beginning prior to the EVA itself, Tools Logistics, Procedure Review, etc (everything up to EVA prep on EVA day)
  - _12.25_ hrs. of Crew Time is required on average for OFV
  - _12.42_ hrs. of Crew Time is required on average for EVA prep
    - On EVA day minus time out EVA – includes 2 EV and 1 IV)
  - _0.9_ lbm O2 per suit per IV Activity - ALCLR (Loop Scrub)
  - _0.15_ lbm O2 per suit per IV Activity – On-Orbit Fit Verification (OFV)*
  - _5.13_ lbm O2 ISLE Prebreath Protocol gas loss per suit/crewmember
  - _1.0_ lbm Air residual Airlock depress gas loss
  - _0.80_ lbm O2 per suit for post EVA recharge
  - EVA Consumables *lost during the EVA itself*
    - _0.89_ lbm O2 per suit per EVA (lost to EMU Suit Leaks and Met Rate)
    - _4-6_ lbm H20 assumed per suit per EVA (Sublimator Cooling Water recharge, ullage)
    - _2_ lbm (32 oz) H20 drinking water per Crew per EVA**
    - _____ W*h Battery Recharge (post EVA)
    - _____ W*h MetOx Regen Oven (post EVA)
    - _6:39_ h Crew Time of the EVA itself (time not spent doing other things)
  - _15.83_ hrs. of Crew Time is required on average for post EVA servicing
    - After the EVA itself, cleaning the EMU, re-stowing all components and tools, recharge/refill operations, etc

***OFV's only occur once per crew for their time on orbit, NOT every EVA a given crew member conducts**

**** Drinking water is not actually tallied in the bottom line summary b/c it would have otherwise been consumed with or without the EVA by the human**

Extravehicular Activity Management Office

Vehicle Consumables

- **Representative screenshot (portion)from excel file on O2 consumables**

O2 Use for EMU EVA

Average O2 use per crewmember per EVA:	0.89	
Average time EVA:	6:39	6.65
Average O2 use per crewmember per EVA hour:	**0.13**	

EVA	PET	Total O2 Used (lbm)	EV1 O2 Use (lbm)	EMU 1 ΔP (psi)	EV2 O2 Use (lbm)	EMU 2 ΔP (psi)	LiOH/METOX	Reference
US EVA 31	5:38	1.69		549		530		N103086
US EVA 30	6:43	1.89		643		569		N102992
US EVA 29	6:41	1.95		629		618		N102895
US EVA 28	6:34	1.73		536		573		N099673
US EVA 27	6:13	1.52		520		454		N099451
US EVA 25	7:30	1.8		598.8		566.3		N092019
US EVA 24	5:28	1.4		385.5		490.3		N092019
US EVA 22	6:07	1.7	0.92	588	0.78	502		N086684
US EVA 20	6:38	1.56	0.75	481	0.81	516		N080773
US EVA 19	6:28	1.4	0.64	410	0.76	485		N079285
US EVA 18	8:17	1.78	0.93	600	0.85	543		N079104
STS-135 EVA 1	6:31	1.72	0.93	595	0.79	507		N069958
STS-134 EVA 4	7:24	2	0.86	549	1.14	546		N068471
STS-134 EVA 3	6:54	1.83	0.89	572	0.94	601		N068347
STS-134 EVA 2	8:07	2.01	1.01	648	1	643		N068184A
STS-134 EVA 1	6:19	1.91	0.84	535	1.07	682		N068098
STS-133 EVA 2	6:14	1.86	0.86	550	1	641		N065730
STS-133 EVA 1	6:34	1.85	0.84	543	1.02	650		N065594
US EVA 17	7:20	1.74	0.97	622	0.77	495		N060589
US EVA 16	7:26	1.64	0.95	609	0.69	440		N060489
US EVA 15	8:03	2.07	1.2	770	0.87	555		N060390
STS-132 EVA 3	6:46	1.54		479		508		N058211B
STS-132 EVA 2	7:09	1.87		687		512		N058063
STS-132 EVA 1	7:25	1.9		510		705		N057928A
STS-131 EVA 3	6:24	1.61	0.82	526	0.79	505		N056313
STS-131 EVA 2	7:26	1.84	0.92	592	0.92	590		N056153
STS-131 EVA 1	6:27	1.8	0.93	597	0.87	556		N055951
STS-130 EVA 3	5:48							
STS-130 EVA 2	5:54	1.81	0.9	572	0.91	515		N053607A
STS-130 EVA 1	6:32	1.87	1.07	682	0.8	515		N053485A
STS-129 EVA 3	5:42	1.46						N050499
STS-129 EVA 2	6:08	1.85						N050368
STS-129 EVA 1	6:37	1.84						N050209
STS-128 EVA 3	7:01	1.79	0.84	597	0.65	552		N046887A
STS-128 EVA 2	6:39	1.49	0.84	539	0.65	416		N046723