

Mars Surface Tunnel Element Concept

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Abstract— How Mars surface crews get into their ascent vehicle has profound implications for Mars surface architecture. To meet planetary protection protocols, the architecture has get Intravehicular Activity (IVA)-suited crew into a Mars Ascent Vehicle (MAV) without having to step outside into the Mars environment. Pushing EVA suit don/doff and EVA operations to an element that remains on the surface also helps to minimize MAV cabin volume, which in turn can reduce MAV cabin mass. Because the MAV will require at least seven kilograms of propellant to ascend each kilogram of cabin mass, minimal MAV mass is desired.

For architectures involving more than one surface element—such as an ascent vehicle and a pressurized rover or surface habitat—a retractable tunnel is an attractive solution. Beyond addressing the immediate MAV access issue, a reusable tunnel may be useful for other surface applications once its primary mission is complete.

A National Aeronautics and Space Administration (NASA) team is studying the optimal balance between surface tunnel functionality, mass, and stowed volume as part of the Evolvable Mars Campaign (EMC). The “Minimum Functional Tunnel” is a conceptual design that performs a single function. Having established this baseline configuration, the next step is to trade design options, evaluate other applications, and explore alternative solutions.

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1. INTRODUCTION

The National Aeronautics and Space Administration’s Evolvable Mars Campaign (EMC) [1] is an ongoing series of architectural trade analyses to define the capabilities and elements needed for a sustainable human presence on the surface of Mars.

Crewed Mars Surface Mission

As currently envisioned in the EMC framework, a crewed surface mission begins with delivery of the crew’s return vehicle, called the Mars Ascent Vehicle (MAV, Figure 1). To save landed mass, the MAV lands on Mars with empty liquid oxygen propellant tanks more than a year before the crew arrives and extracts oxygen from the Martian atmosphere. When the MAV’s propellant tanks are confirmed full, the crew lands and spends up to 500 sols working on the Martian surface. At the end of their surface mission, the crew transfer into the MAV and departs.



Figure 1. Mars Ascent Vehicle Conceptual Design

Why Do We Need A Tunnel?

Because the MAV is never used for habitation, it remains unused until the final sol of the surface mission. This keeps the MAV’s crew cabin free from surface dust, and serves an important role in providing planetary protection back to Earth [2]. But how do we keep the crew from tracking Martian dust into the MAV? If the crew were to simply walk from their surface habitat to the MAV, open the hatch and climb aboard, the MAV cabin would be directly exposed to the surface, plus the crew would ascend wearing dusty Extravehicular Activity (EVA) space suits. To meet planetary protection protocols, the architecture has to do two things: 1. Allow crew to ingress the MAV without exposing the cabin directly to the surface and, 2. Facilitate crew ingress to the MAV wearing clean Intra-vehicular activity (IVA) pressure suits that have never been outside a pressure cabin. Pushing EVA suit don/doff and EVA operations to an element that remains on the surface also helps to minimize MAV cabin volume, which in turn can reduce MAV cabin mass. Because the MAV will require at least seven kilograms (kg) of propellant to ascend each kilogram of cabin mass [3], minimal MAV mass is desired.

Although there are numerous alternatives, a retractable, pressurized tunnel from a pressurized rover (Figure 2) was presumed to be the simplest, lowest mass option.



Figure 2. Mars Pressurized Rover Conceptual Design

Study Objectives

The primary objective of this study was to define surface tunnel functional requirements for the purpose of trading various MAV ingress/egress options. A secondary objective was to identify potential alternative uses for a surface tunnel, once its primary mission was complete.

Study Approach

The study team began by identifying the minimum set of functional requirements needed for the tunnel to perform its primary mission, as this would presumably be the simplest design, with the lowest mass and volume. This Minimum

Functional Tunnel then becomes a baseline against which various tunnel design concepts—and potential alternatives—could be traded.

2. MINIMUM FUNCTIONAL TUNNEL

The “Minimum Functional Tunnel” is a conceptual design that performs a single function: getting IVA-suited crew from a pressurized rover into the MAV without having to step outside into the Mars environment. If this minimum functional tunnel mass and volume fits within available lander stowage allocations, then additional “bells and whistles” that might allow the tunnel to perform other jobs may be considered. If not, then the minimum functional tunnel mass and volume will be traded against alternative approaches.

Minimum Functional Requirements

At a minimum, the surface tunnel must:

- R1. Provide a controlled environment between the MAV and pressurized rover.
- R2. Provide an environmental seal around ingress-egress hatches on both the MAV and pressurized rover.
- R3. Provide sufficient internal volume for passage of up to four crew members (not necessarily all at the same time) wearing IVA suits.
- R4. Provide sufficient crew interface devices (such as handrails) to facilitate crew translation.
- R5. Provide a means of aligning with the rover.
- R6. Provide a means for detaching from the MAV.

The lander descent stage serves as the MAV’s launch pad structure, so the MAV must remain elevated on top of the descent stage after landing, as shown in Figure 3. Assuming current design concepts, this vertical difference places the MAV hatch approximately 2.6 m higher than the rover hatch (assuming both are on level terrain), which drives one additional tunnel function:

- R7. Accommodate a relative elevation difference between the MAV and rover.

It should be noted that this elevation mismatch applies not only for rover-to-MAV translation, but potentially also to rover-to-habitat translation if the surface habitat remains on top of its lander.

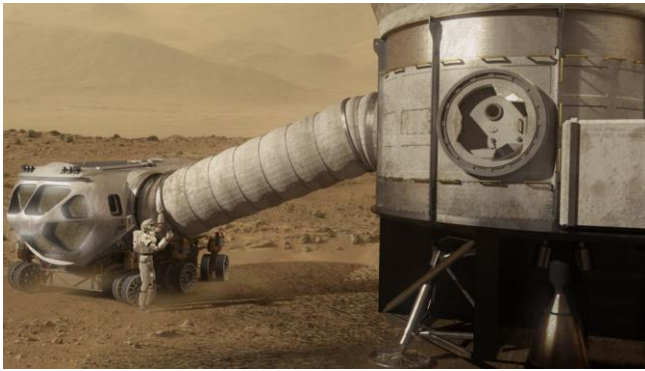


Figure 3. Rover-to-MAV Surface Tunnel Concept

General Concept of Operations

The following general concept of operations was developed to facilitate minimum functional tunnel definition:

The surface tunnel is attached at the MAV’s ingress/egress hatch on Earth, and remains attached through Earth launch, transit, Mars entry, descent, and landing. The tunnel is unused until the crew prepare for departure. A few days before crew departure, a two-person MAV check-out crew transfers from their surface habitat to the pressurized rover, and drives to the MAV. The check-out crew deploys the tunnel and attaches it to the pressurized rover’s ingress/egress hatch, and verifies the tunnel is environmentally sealed from surface dust. Wearing clean IVA suits, the check-out crew translate from the pressurized rover to the MAV to stow return cargo and perform MAV pre-flight inspections. Upon completion of MAV preparations, the check-out crew retreats back through the tunnel to their pressurized rover, closing the tunnel hatch before detaching and driving back to the habitat. After securing the surface habitat, all four crew transfer from their surface habitat to the pressurized rover, drive to the MAV, and re-dock with the tunnel. After translating from the pressurized rover to the MAV in their clean IVA suits, the crew detaches the tunnel from the MAV and departs Mars.

3. TUNNEL DESIGN CONSIDERATIONS

There are numerous implementation strategies to meet the seven functional requirements identified above, but the following design considerations should be addressed.

R1. Controlled Environment

The surface tunnel must allow crew to translate between a pressurized rover and the MAV without being exposed to Martian dust, requiring a passageway of some sort between the two vehicles that is impervious to the Martian environment. There are numerous implementation options to do this, ranging from a fixed, rigid structure to inflatables or convoluted retractable devices.

Technically, the tunnel could be designed for shirt-sleeve translation, but at some point the crew must don IVA suits for ascent and there will be more elbow room to do this in the rover than in the MAV. If the crew are wearing IVA suits, the tunnel does not necessarily have to be pressurized, though there are several reasons to do so. First and foremost, positive pressure inside the tunnel reduces the chance that Martian dust will leak in. Second, if the tunnel is pressurized below suit minimum pressure, then the crew will have to translate wearing gloves and helmets, in an inflated suit—which is much more difficult than wearing an unpressurized suit and carrying helmet and gloves. Finally, a pressurized tunnel opens up the design space—for example, an inflatable tunnel design might not be rigid enough for crew translation if the differential pressure is too low. There are at least four options for pressurizing the tunnel: a self-contained system (though that adds mass and complexity to the tunnel), pressurize from the MAV (though that adds mass to the MAV), pressurize from the rover, or some combination of these options (for example, equalize pressure between the MAV and rover). Note that current MAV and rover concepts both operate at 56.5 kilo Pascals (kPa) pressure. If the tunnel is pressurized, the integrated design must take into account pressurization loads on the MAV and rover.

R2. Hatches

Regardless of what internal pressure the tunnel operates at, it must provide an environmental seal around both the MAV and rover hatches. Current design concepts specify the same hatch on both vehicles, measuring 1 meter (m) x 1 m square (Figure 4). This allows both ends of the tunnel to be identical.

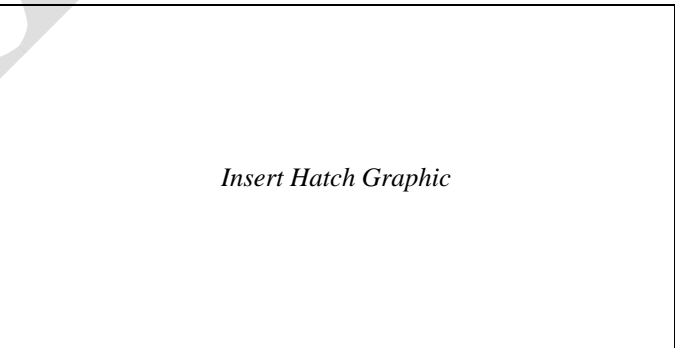


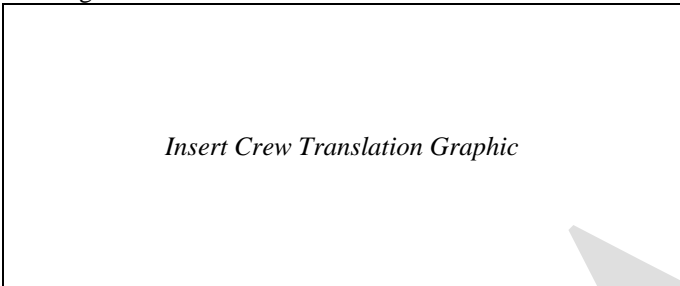
Figure 4. MAV and Pressurized Rover Hatch Concept

The MAV end of the tunnel arrives pre-connected, but the rover end of the tunnel would be exposed without at least a dust cover installed. Depending on how the tunnel is operated, it may be prudent to include a pressure hatch on the rover end to avoid loss of pressure between uses. In that case, the design must be coordinated with the rover team to mitigate hatch swing interference between the two elements.

R3. Internal Volume

Tunnel volume is a function of tunnel cross-sectional area and length. To minimize structural mass and oxygen consumables (if the tunnel is pressurized), the tunnel volume should be as small as possible. At a minimum, the cross section must be large enough for a single IVA-suited crew member to slide through in a horizontal position (such as shown in Figure 5). Larger cross sections that would allow crew to crawl or even walk upright are possible but would likely add significant mass to the design.

Another consideration is whether cargo or equipment will be transferred through the tunnel. The current EMC baseline specifies 250 kg of cargo returning with the MAV. For the purpose of this exercise, the study team assumed that the largest piece of equipment passing through the tunnel would be a crew seats, measuring approximately 0.88 m deep x 1.5 m long x 0.7 m wide.



Insert Crew Translation Graphic

Figure 5. Crew Translation

R4. Crew Interfaces

In microgravity, handrails are sufficient for crew translation through a long tunnel (Figure 6), but in Mars gravity the crew will be in contact with the bottom of the tunnel. Crew interfaces will depend on several factors, including whether the tunnel is sized for sliding, crawling, or walking, whether the structure is rigid or inflatable, whether the tunnel is horizontal or at an incline, and whether the tunnel is a smooth bore or a convoluted structure. An internal ladder may be needed if the tunnel is at a steep incline. For sliding crew, options include using a winch to pull each crew member through the tunnel or mounting a pair of rails inside the tunnel attached to a sliding translation seat. Regardless of the translation method, crew interfaces will add some mass to the tunnel assembly and must be accounted for.

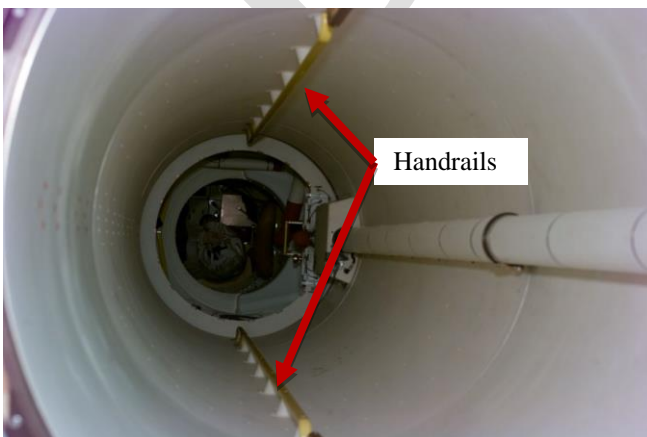


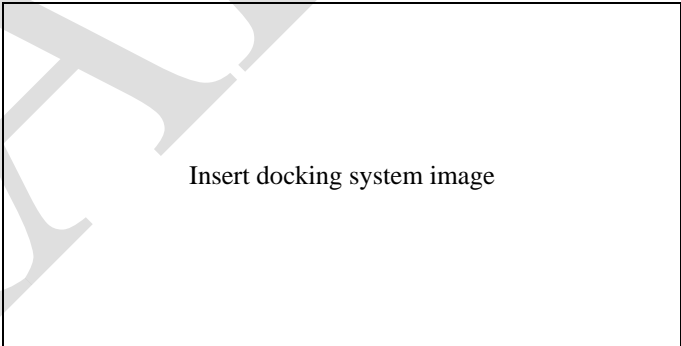
Figure 6. Tunnel Crew Translation Aids

R5. Rover Hatch Alignment

Current rover concepts offer approximately +/- 2.5 cm of fine adjustment, so additional alignment capability is likely needed. This may be accomplished by provisions inherent on in the tunnel design (potentially adds mass), or through external means, such as a robotic arm mounted on the rover or lander (more complicated, but if the rover or lander already carry a robotic arm, there is no additional mass penalty).

R6. Docking

Regardless of how the tunnel is manipulated into position, it must then provide a means for one end to attach to the rover and later detach the other end from the MAV. On the MAV end, the lowest mass solution may be a pyrotechnic device that severs the connection, though this would preclude re-use of the tunnel after the MAV departs. Because the rover is intended for use over multiple expeditions, the rover end of the tunnel will require a reusable solution. This may be as simple as a manual latching system, or as complex as an active docking system (Figure 7).



Insert docking system image

Figure 7. NASA Standard Docking System

R7. MAV and Rover Relative Positions

To balance the lander, the large, heavy MAV is positioned in the center of an approximately 9 m diameter lander deck. If the rover parks as close to the lander as possible, the sharp tunnel angle between the two would clip the edge of the lander deck as shown in Figure 8. Simply removing this portion of lander deck solves the issue, but because the descent engines and propellant tanks are mounted under the deck, this may not be possible.

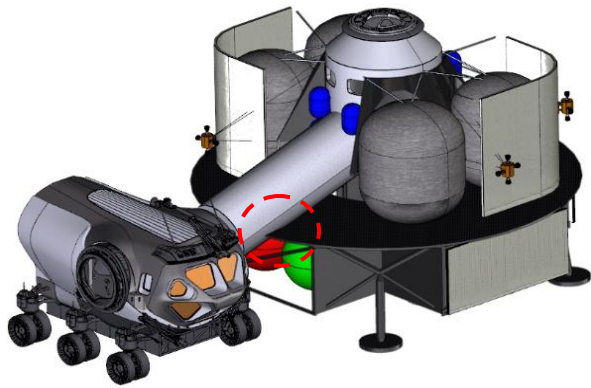


Figure 8. Lander Deck/Tunnel Interference

A second option is to park the rover farther away from the lander, giving the tunnel a shallower angle that allows it to clear the deck, as shown in Figure 9. However, this makes the tunnel approximately 7.11 m long and poses a new set of challenges related to tunnel mass, stowage volume, and ease of handling.

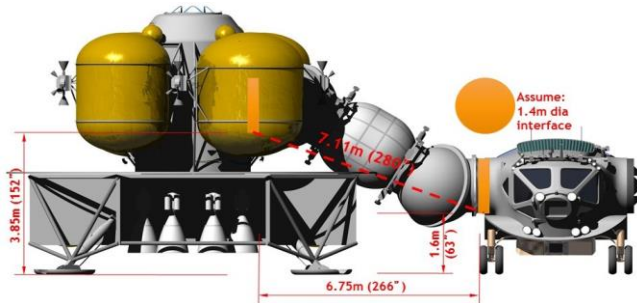


Figure 9. Shallow Tunnel Angle (need simplified graphic)

A third option is to raise the rover's elevation, but this would require significant internal rover chassis adjustability or external means such as modifying the terrain, or employing a ramp, jack or other equipment—all adding mass, complexity, and risk.

A fourth option is to employ a segmented tunnel that can articulate around the lander deck obstacle, such as shown in Figure 10, though this may also add considerable mass.

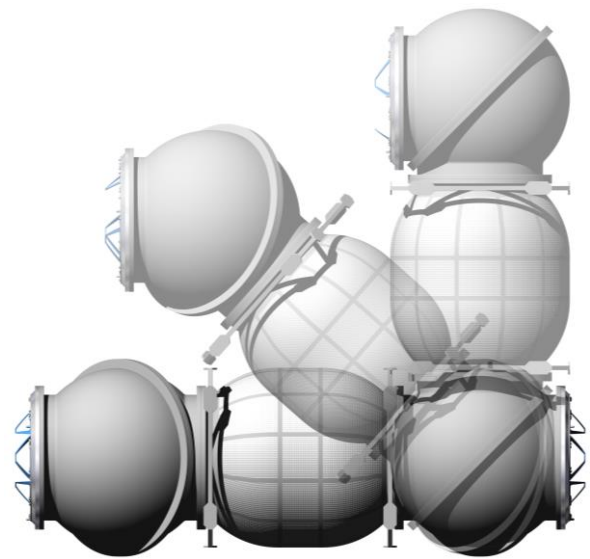


Figure 10. Articulating Tunnel

4. MINIMUM FUNCTIONAL TUNNEL CONCEPT

Assumptions

To further refine the tunnel concept, the study team made the following assumptions based on preliminary MAV and rover concepts, known operational constraints, and many of the design considerations outlined above:

- A1. The tunnel arrives with one end pre-attached to the MAV.
- A2. Tunnel is used for both crew and equipment translation.
- A3. Tunnel must be large enough to allow passage of equipment up to 0.88 m deep x 1.5 m long x 0.7 m wide.
- A4. Tunnel must accommodate crew physical stature and mass per Orion Multipurpose Crew Vehicle (MPCV) requirements [4].
- A5. Services to the tunnel (power, thermal control, ventilation, etc.) are not provided by the tunnel element itself.
- A6. The tunnel is not used before the crew arrives.
- A7. The tunnel must accommodate 1 m x 1 m square pressure hatches on either end.
- A8. The tunnel must operate at positive pressure relative to the Mars surface, to prevent dust from leaking into the tunnel.
- A9. If pressurized for shirt-sleeve translation, the tunnel must operate at 56.5 kiloPascals (kPa) differential pressure, and materials must be compatible with an internal atmospheric oxygen concentration of 34%.
- A10. Tunnel must accommodate an incapacitated crew member, but it was assumed that incapacitated crew could be pulled via winch from either end of

the tunnel without a second crew member inside the tunnel.

- A11. Tunnel must perform at least three rover mate/demate cycles, including pre-launch MAV preparation.
- A12. Tunnel must meet a minimum 10 year life cycle from Earth launch to disposal, with at least four years of that life cycle on the Mars surface.

Conceptual Design

Conceptual design depends on the implementation path selected to address the various functional requirements. Figure 11 outlines the trade tree of design options, with the highlighted options providing the minimum functionality that is presumed to represent the lowest mass penalty.

Insert minimum functional tunnel design description (as shown in Figure 12).

Estimated Mass

Insert mass estimate

Estimated Stowed Volume

Insert volume estimate

5. ALTERNATE USES

After investing in a surface tunnel, re-using it will be more cost-effective than discarding the tunnel after its primary mission is complete. The most obvious opportunity is to manifest one tunnel and re-use it for subsequent MAV missions, though this adds new functional requirements to the design: the tunnel would have to be mobile, and capable of more mate-demate and usage cycles. Actual mobility function does not necessarily have to be provided by the tunnel itself but it must have lifting eyes, grappling fixtures, or other means to accommodate the lander's cargo off-loading system or even manual handling by EVA-suited crew, and it would have to fit onto a surface mobility system for relocation.

Figure 11. Trade Tree

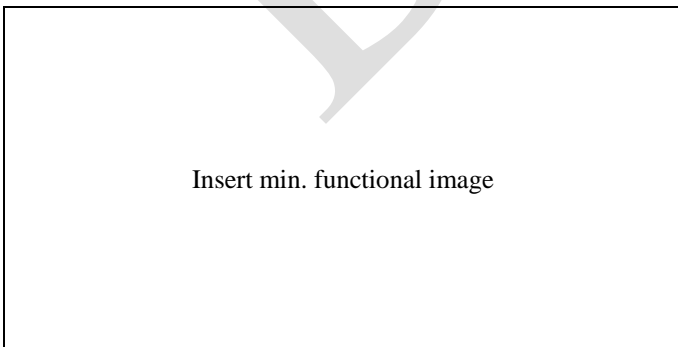


Figure 12. Minimum Functional Tunnel Concept

The study team also explored applications beyond the primary rover-to-MAV case.

Habitat-to-Rover Transfer

Notionally, EMC operational concepts envision a rover docking to the surface habitat for crew transfers. As noted above, if the habitat remains on top of a lander, vertical misalignment between the two vehicles may lend itself to a transfer tunnel of some sort, similar to the MAV-to-rover case. Re-purposing the MAV tunnel for this application adds two important functional requirements: accommodate larger hatches and higher internal pressures.

Current surface habitat concepts envision a large 1 x 1.5 m hatch to accommodate frequent ingress/egress. This would

require one end of the tunnel to be larger than the other end, increasing tunnel mass and handling complexity. Current pressurized rover and MAV concepts are matched for nominal operation at 56.5 kPa cabin pressure, and can both tolerate cabin depressurization, whereas current surface habitat concepts operate at 101 kPa, with nominal depressurization more problematic. Therefore, the surface tunnel would also have to meet higher differential pressure requirements (which would slightly increase its mass) if repurposed for rover-to-Habitat operation.

Habitat-to-Habitat Transfer

One architecture trade being studied by the EMC is a single, monolithic surface habitat versus multiple modular habitats. A pressurized tunnel would allow shirt-sleeve translation between multiple modules [5]. Although a single monolithic habitat could remain on top of its lander descent stage, modular habitats would likely be offloaded and positioned near each other. This would eliminate the lander deck interference issue noted in the nominal usage case, and could allow for much shorter tunnels between habitat modules. For re-use in this application it would make sense to employ a segmented rover-to-MAV tunnel assembly that could be broken into shorter sections for habitat-to-habitat use. However, this would likely add mass, and each tunnel segment joint would become a potential pressure or dust leak path. Also note that in this application, both ends of the tunnel would have to accommodate the larger habitat hatches. Although crawling or sliding through a small diameter tunnel is acceptable for the infrequent rover-to-MAV usage, frequent (many times per sol) translations between habitat modules would be more comfortable if the tunnel diameter could accommodate upright walking, making the tunnel oversized for its primary rover-to-MAV mission. What's more, the tunnel would have to be maintained at the habitat's higher pressure for much longer periods of time, likely resulting in more stringent reliability requirements.

Habitat-to-Logistics Module Transfer

EMC architectures envision pressurized logistics modules (Figure 13) to deliver crew provisions, spare parts, and science equipment. Ideally, these containers would be attached directly to a surface habitat port. If direct connection is not possible, a pressurized tunnel might be useful. A tunnel used for this application would require the same functionality noted above for the habitat-to-habitat or habitat-to-rover cases.

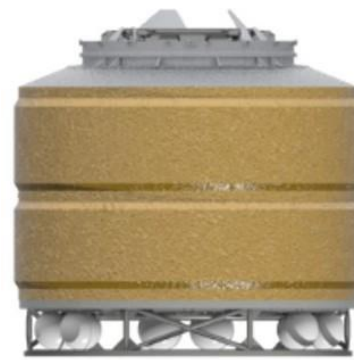


Figure 13. Logistics Module

Rover-to-Rover Transfer

Another potential tunnel application is to join two pressurized rovers together. As with the modular habitat-to-habitat case, both rovers would be at the same elevation allowing for a relatively short tunnel. However, unlike habitat applications, a rover-to-rover tunnel only needs the smaller MAV-sized hatches on both ends and could operate at 56.5 kPa or lower internal pressure. The problem is that this application would likely only be used during rover excursions far from the lander base—which means that either the tunnel must have an ability to deploy/retract itself, or the rovers must carry a tunnel handling mechanism. Either way, this application adds cargo mass to the rovers which likely reduces their excursion distance per sol.

Habitat- or Rover-to-Laboratory

To preserve the integrity of collected Martian samples and facilitate planetary protection, the architecture may include a science laboratory that is completely separate from the habitat. If the laboratory is pressurized then a habitat- or rover-to-laboratory tunnel would require similar functionality to the habitat-to-habitat or rover-to-habitat cases previously discussed. But unlike the other elements discussed here, the science laboratory may not actually be pressurized. What's more, scientists may prefer robotic sample handling rather than shirt-sleeve or even EVA-suited crew handling. In this case, there is no need for a tunnel.

Contingency Uses

The study team explored two potential contingency uses for a surface tunnel when attached to a habitat: as an emergency airlock, or as an emergency safe haven. To use a surface tunnel for either of these contingency cases adds two significant new functions to the design: the tunnel itself must provide services (particularly oxygen and power) since there is a presumption that the mating vehicle is disabled, and the tunnel must be large enough to accommodate the larger, bulkier EVA suits. The study team quickly concluded that a surface tunnel is not the optimum element to address these contingencies.

6. FORWARD WORK

Tunnel Trades

Given the minimum functional tunnel concept—which is presumably the simplest, lowest mass and volume design—the study team will be able to trade various design options across the expanded list of operational concepts and alternative uses.

Tunnel Alternatives

A minimum functional tunnel may be an adequate solution for a one-mission problem, but may not be optimum over a multi-mission surface campaign. The following tunnel alternatives will be traded against tunnel concepts for mass, operational complexity, and risk.

EVA Hatch—EVA hatches have the benefit of relatively low mass and high Technology Readiness Level (TRL). But an EVA hatch would require MAV depressurization for every ingress/egress, and the MAV would have to be big enough for all crew members to don/doff their EVA suits together. Altair project mockup testing [6] found that even three EVA suited crew could stand together in a relatively small 1.8 m diameter cabin. However, getting into and out of their EVA suits was hampered by a rear-entry suit design that requires the PLSS hatch to swing open laterally for suit doffing (Figure 15). In practice, this either forces the cabin diameter to grow to accommodate PLSS hatch swing, or it will drive a fundamental design change to the EVA suits. These issues aside, the biggest drawback to an EVA hatch is that it will be virtually impossible to keep dust out of the MAV. Apollo experience [7] warns that opening an EVA hatch directly to the surface will bring dust into the ascent vehicle, which drives MAV cabin design and equipment mass to prevent Martian dust from migrating back into the transit vehicle and eventually to Earth.

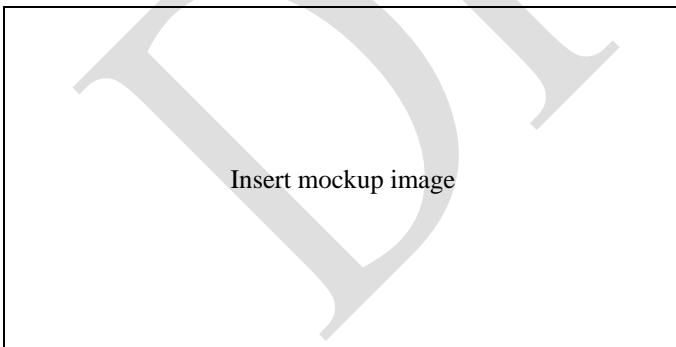


Figure 15. EVA Suit Hatch Interference

Airlock—An airlock module provides better dust mitigation than an EVA hatch, but would still place dusty EVA suits in close proximity to an open MAV hatch. As dust settles to the Airlock floor, some means to keep IVA-suited crew from tracking the dust into the MAV would also be required.

Suitport—Suitports (Figure 16) offer the promise of dust mitigation by keeping dusty suits entirely outside the pressure cabin, but current protocol still requires an EVA hatch to get the suits outside for the first EVA, and back inside after the final EVA. This is primarily because current designs don't provide enough structural support to protect the suits from ascent/descent loads or potential thruster plume impingement. Concepts to address these problems have been proposed, but add even more mass to each suitport (which are already about 100 kg each). Even if the structural problem is resolved, an EVA hatch is still required for an incapacitated crew member contingency, since it may not be possible to pull an unconscious person up through the suit's rear-entry hatch to safety.



Figure 16. Suit Port Concept

At nearly one meter centerline-to-centerline spacing between suitports, a small MAV cabin diameter is unlikely to provide sufficient real estate for more than two suit ports. This poses operational timeline impacts in getting more than two crew members in or out of the vehicle. Crews could ingress two at a time, but once the first two are inside, their suits would have to be removed from the suitports before the next two crew members could ingress. Once detached from the suit port, an empty suit can be damaged if the water inside freezes, which means additional thermal conditioning mass will be needed outside the vehicle for suit stowage—exacerbating what is already a poor mass trade for the suit ports. Worse, to protect against a contingency where the MAV engines fail to ignite and crew need to retreat back to a habitable element, the MAV may have to keep one or two EVA suits attached to its suitports until lift-off, further adding complexity and mass.

Suitport-Airlock—One compromise solution is the Suitport-Airlock (Figure 17), sometimes referred to as a Suitlock. This provides the best of both worlds, but at considerably higher mass than either individual option. As compared to a reusable tunnel that is relocated after the MAV departs, the Suitport-Airlock may trade well, assuming that it can be relocated as readily as a tunnel could.

3.5 m diameter Hab with planar suitport bulkhead

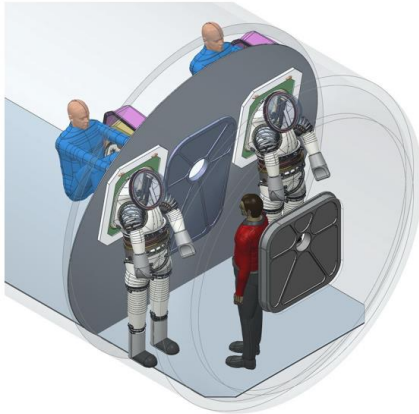


Figure 17. Suit Lock Concept

8. CONCLUSIONS

How Mars surface crews get into their ascent vehicle has profound implications for Mars surface architecture. To meet planetary protection protocols, the architecture has to do two things: 1. Allow crew to ingress the MAV without exposing the cabin directly to the surface and, 2. Enable crew in the MAV to wear clean IVA suits that have never been outside a pressure cabin. Pushing EVA suit don/doff and EVA operations to an element that remains on the surface also helps to minimize MAV cabin volume, which in turn can reduce MAV cabin mass. Because the MAV will require at least seven kilograms of propellant to ascend each kilogram of cabin mass, minimal MAV mass is desired.

For architectures involving more than one surface element—such as an ascent vehicle and a pressurized rover or surface habitat—a retractable tunnel is an attractive solution. Beyond solving the immediate MAV access issue, a reusable tunnel may be useful for other surface applications once its primary mission is complete.

A NASA team is studying the optimal balance between surface tunnel functionality, mass, and stowed volume as part of the EMC. The “Minimum Functional Tunnel” is a conceptual design that performs a single function: getting IVA-suited crew from a pressurized rover into the MAV without having to step outside into the Mars environment. Having established this baseline configuration, the next step is to trade design options, evaluate other applications, and explore alternative solutions.

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BIOGRAPHY



Michelle Rucker received a B.S. and in Mechanical Engineering from Rice University in 1984 and a MA in 1986. She has been with NASA for 29 years. She currently serves in the Exploration Integration and Science Directorate at the Johnson Space Center. She began her NASA career as a test engineer at the White Sands Test Facility before moving onto roles as a deputy subsystem manager for the International Space Station, EVA and Spacesuit Systems Deputy Branch Chief, and Altair Lunar Lander Test and Verification Lead.



Scott Howe, PhD. Bio.



Natalie Mary, Bio.



Sharon Jefferies, Bio.

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