Design Concept for a Minimal Volume Spacecraft Cabin to Serve as a Mars Ascent Vehicle Cabin and Other Alternative Pressurized Vehicle Cabins

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Abstract - *The Evolvable Mars Campaign is developing concepts for human missions to the surface of Mars. These missions are round-trip expeditions, thereby requiring crew launch via a Mars Ascent Vehicle (MAV). A study to identify the smallest possible pressurized cabin for this mission has developed a conceptual vehicle referred to as the minimal MAV cabin. The origin of this concept will be discussed as well as its initial concept definition. This will lead to a description of possible configurations to integrate the minimal MAV cabin with ascent vehicle engines and propellant tanks. Limitations of this concept will be discussed, in particular those that argue against the use of the minimal MAV cabin to perform the MAV mission. However, several potential alternative uses for the cabin are identified. Finally, recommended forward work will be discussed, including current work in progress to develop a full scale mockup and conduct usability evaluations.*

Keywords: Mars, human factors, habitability, rover, habitat, spacecraft.

1 Introduction

1.1 Evolvable Mars Campaign

The Evolvable Mars Campaign is a NASA study team established to "Define a pioneering strategy and operational capabilities that can extend and sustain human presence in the solar system including a human journey to explore the Mars system starting in the mid-2030s." [1] Figure 1 graphically depicts a series of technical advances the Evolvable Mars Campaign has determined will help NASA advance from low Earth orbit to the surface of Mars.

Current Evolvable Mars Campaign assumptions anticipate a single site on Mars for all human surface missions. [2] This results in a campaign architecture where a Mars Ascent Vehicle (MAV) is deployed to the Mars surface in advance of the crew and is prepared for launch prior to the crew's arrival.

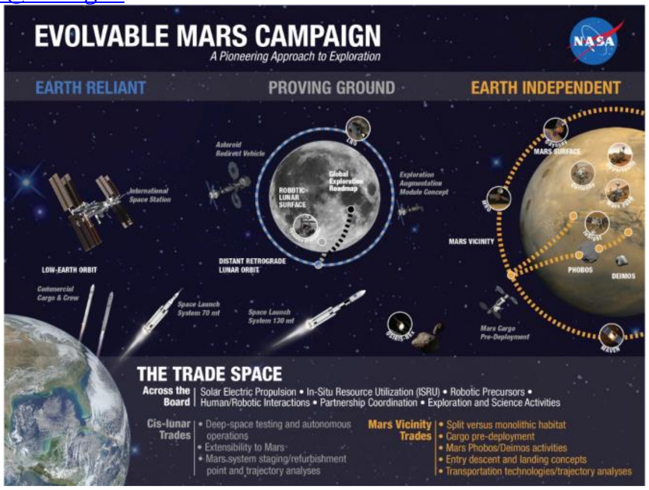

Figure 1. Evolvable Mars Campaign

1.2 Mars Ascent Vehicle Mission

The MAV is used to launch the crew into space and deliver them either to the Mars Transfer Vehicle that is loitering in a high Mars orbit during the surface portion of the Mars expedition, or to a Mars Taxi that is loitering in low Mars orbit waiting for the MAV. In the latter case, the taxi would be responsible for transferring the crew from this low Mars orbit to the Mars Transfer Vehicle.

If the MAV is only required to deliver the crew to a waiting taxi in low Mars orbit then the total mission time inside the MAV is on the order of 12-18 hours. This will enable the smallest possible (and therefore lightest) MAV cabin. Particularly, many crew systems will not be required in the cabin. These mass savings will in turn enable smaller propellant tanks on the ascent vehicle.

However, if the MAV is required to deliver the crew all the way to the Mars Transfer Vehicle then the total mission time inside the MAV is on the order of 3-5 days. This means the MAV will require a complete outfitting of crew systems, including crew sleep, waste and hygiene, galley, and meaningful crew work.

2 Background

2.1 HAT MMSEV MAV Study

In support of the Evolvable Mars Campaign, the NASA Human Spacecraft Architecture Team (HAT) has commissioned a MAV study to be conducted by the Multi-Mission Space Exploration Vehicle (MMSEV) project team. This study was directed to consider commonality approaches between the MMSEV and MAV.

2.1.1 MMSEV Overview

The MMSEV began its life as a pressurized lunar rover under the now-defunct NASA Constellation program. Known most prominently as the Lunar Electric Rover (LER) the MMSEV was conceived to allow a two-person crew to conduct sorties up to 14 days in duration away from a lunar surface outpost. Following the conclusion of the Constellation program, the MMSEV program adapted the LER cabin to also serve as the cabin for a small spacecraft to explore a deep space asteroid, or to serve as an airlock for a Cislunar space station, or to serve as a lunar lander and ascent vehicle cabin. This multi-mission commonality approach could potentially result in significant cost savings for a Mars expedition if the MMSEV cabin can be used in the Mars architecture.

2.1.2 MAV Blue Sky Brainstorming

A two-day brainstorming session explored the mission of the MAV and reviewed MMSEV developments to date. During the brainstorming a variety of questions and concepts emerged, with the primary result being two distinct schools of thought: a MAV cabin could either be designed to be highly common with the MSEV cabin, or a MAV cabin could be designed to be the smallest (therefore lightest) vehicle possible. This paper will explore the second option. The basis for this configuration is a cylindrical spacecraft with a diameter driven by a 2 x 2 matrix of seated crew and hemispherical endcaps, shown in Figure 2. The resulting cabin is approximately 73 inches in diameter and 134 inches in length.

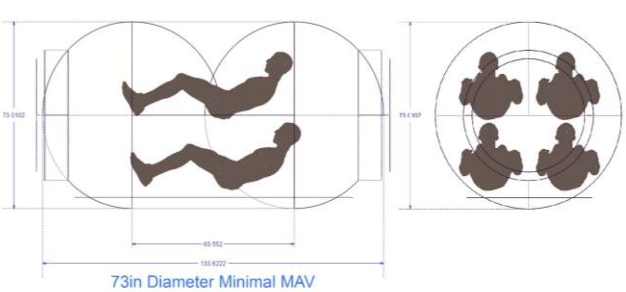

Figure 2. Sizing Basis for Minimal MAV Cabin

3 Minimal MAV Cabin Configuration

A refined interior of the Minimal MAV Cabin is shown in Figure 3, as envisioned by MMSEV project team industrial designers. Several key features of this minimal volume spacecraft cabin (MVSC) will be briefly described.

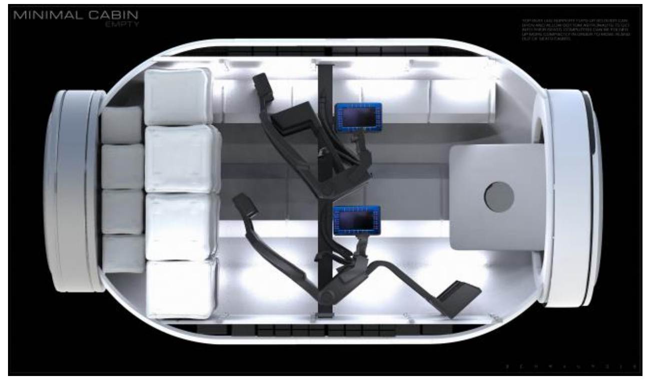

Figure 3. Minimal Volume Spacecraft Cabin

The MVSC has dual docking ports, at the front and back of the cabin. Each docking port contains a 40-inch by 40-inch square hatch with rounded corners. The hatch is surrounded by a marmon flange derived from the MMSEV program [3], to attach to an Active-Active Mating Adapter (AAMA) derived docking system. The AAMA was developed under the NASA Constellation program to dock two lunar rovers together [3] as shown in Figure 4. Also between the hatch and the marmon flange are utility connectors, allowing for power and data exchange once docked. Both docking ports are identical, allowing either end of the spacecraft to dock with appropriately configured surface or in-space assets.

Figure 4. Active-Active Mating Adapter

The cabin diameter is sized to seat four crew in a 2 x 2 vertical configuration as shown in Figure 3. The crew seats are supported by one or more vertical struts between the starboard and port seats. It remains as a future design decision to cantilever the seats off this structure or extend a support beam to the outer sides of the spacecraft. The interface between the seats and this support structure is reversible, allowing the seats to face towards either hatch.

As also shown in Figure 3, the seats can fold when not in use to minimize their intrusion into the habitable volume.

Identical displays and controls are mounted at each seat. A future study will define the exact display and control needs, but an initial baseline is to provide each seat with a single edge key display, a seat-mounted cursor control device, a deployable keyboard, and a rotational hand controller. An auxiliary interface port will allow for peripheral devices such as memory storage units to plug in as needed. This display and control architecture is also reversible along with the seats.

A cargo section is located immediately behind the seats. This volume is sized to accommodate minimal crew supplies and 250 kg surface samples. The cargo section can accommodate two rows of Cargo Transfer Bags (CTBs), each spanning the width of the cabin. Open volume is reserved in front of the seats that partly supports hatch swing, but also accommodates relocation of this cargo volume in the event that the spacecraft orientation is reversed.

Spacecraft subsystems are distributed along the spacecraft exterior and inside the pressure vessel along the contours of the inner cabin walls. ECLSS ducting is positioned to provide fresh air at crew head positions, as well as umbilical connections to crew flight suits. An artist's concept of the fully outfitted and configured interior cabin view with crew in position is shown in Figure 5.

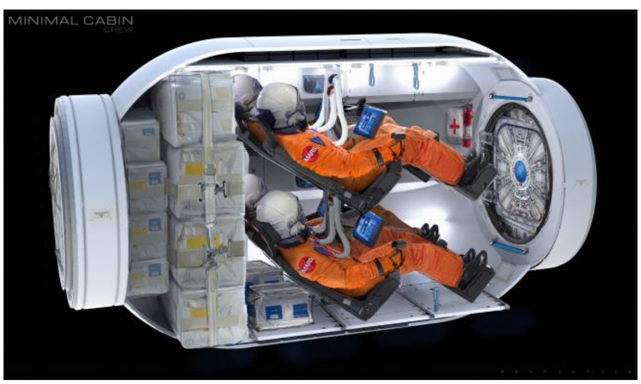

Figure 5. MVSC with Crew Onboard

4 Placement of MAV engine and propulsion tanks

4.1 Configuration Considerations

The MAV consists of more than just the cabin. Structural elements connect the cabin to propulsion tanks, RCS thrusters, and engines. While determining a final configuration is a complex study involving numerous factors, there are several crew considerations that favor specific configurations.

The primary consideration is that the MAV must dock with a surface rover while on Mars and must dock with an in-space transit habitat while in space. Consequently, neither hatch may be blocked. The second consideration is that the MAV cabin is baselined as a horizontally-oriented cabin and should be configured with the tanks, thrusters, and engines as such.

4.2 Configuration Options

4.2.1 Constrained Tank Diameter

Perhaps the most intuitive configuration is to constrain the diameter of the propulsion system to approximately that of the MVSC length, ensuring that there is free access to both hatches. It should be noted that both a surface rover and an in-space vehicle will require some sort of docking tunnel to serve an analogous function to the Active-Active Mating Adapter and the length of that tunnel can be traded against MAV propulsion system diameter.

4.2.2 Drop Tanks with Surface Access

Alternately, rather than constrain the tank diameter, the main engine propellant tanks can be designed to be ejected upon reaching orbit. This will allow the MAV cabin to dock with the in-space transit vehicle, but does not permit the surface rover to dock. Consequently, a longer surface tunnel would be required to cover the distance fro the edge of the propulsion system to the MAV cabin docking port. Presumably, the surface rover or some other surface asset would be responsible for emplacement and removal of this tunnel. Alternately, as a mass-intensive solution the lander might have a drivable deck such that the surface rover could be lifted onto the deck by a crane or large robotic asset and drive over to the MAV cabin to dock with it.

4.2.3 Separable Cabin

Instead of dropping the propellant tanks, the cabin itself could separate and dock to the in-space vehicle. This would assume that the RCS thrusters and tanks, and all other vehicle subsystems excluding the main propulsion subsystem, are attached to the cabin pressure vessel exterior. The surface rover access will still have to be achieved, either with the previously mentioned longer surface tunnel, drivable deck, or with a c.g. management strategy that allows the cabin to placed on one side of the MAV. The latter approach, of course, violates the redundancy management strategy of making both docking ports accessible to the surface rover.

4.3 Configuration Alternative

It should be noted that with significant interior cabin reconfiguration a vertical orientation of the cabin is possible, but may be undesirable. The diameter is not wide enough for an aisle between seats, so the crew will only be able to enter from above the seats, not below them. This would require burying the cabin among the propellant tanks, with the top of the cabin essentially flush with the top of the tanks and an access deck on the top of the MAV for the crew to enter. This is likely not an aerodynamic issue due to the thin Martian atmosphere, but may be a center of gravity issue as the tanks are depleted during ascent.

5 Argument Against MVSC Use as MAV Cabin

The previous sections have demonstrated how a minimal cabin can be used in a Mars Ascent Vehicle. However, there are compelling arguments that suggest it perhaps should not be used in this capacity. Normally, the mantra in spacecraft design is to make the cabin as small as possible under the assumption that doing so will save money. This mantra is pursued most passionately with ascent vehicles because every pound on an ascent vehicle translates to many more pounds in delivery architecture. However, this assumption does not always hold true.

5.1 Cost of Additional Vehicle Program

The first concern is the cost of an additional spacecraft program. There is an unavoidable cost and complexity associated with every unique spacecraft development effort. Given that the Mars architecture is highly cost constrained, it is arguable that a separate cabin should not be developed if any existing cabin can be used in its place. Additionally, the MVSC, while smaller than the MMSEV cabin, is relatively close in size, as shown in Figure 6, and the manufacturing costs associated with setting up a MVSC production facility are likely similar to those that will be expended for a MMSEV production facility.

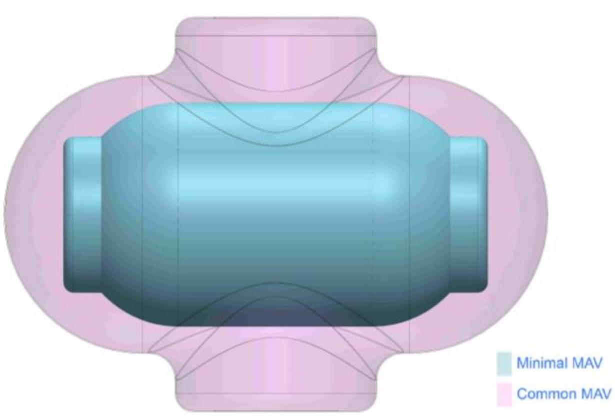

Figure 6. MVSC Overlaid Against MMSEV Cabin

5.2 Mission Duration

More importantly, the minimal MAV cabin is only useful in the mission scenario where the MAV docks with an orbital element within the first 12-18 hours of flight. This is only possible if a spacecraft is waiting for it in Low Mars Orbit. That can only be achieved if either a transfer spacecraft (a taxi of sorts) is maintained in Low Mars Orbit (with associated increased program costs and orbit phasing constraints on when the crew can leave the surface), or if the Mars Transfer Vehicle positions itself in Low Mars Orbit (which would require significant increases in onboard propellant and higher design, manufacturing, and assembly costs). Again, it becomes more expensive to build the smaller MAV cabin than to build a larger cabin with greater capability.

6 Alternate Uses of a MVSC

Given the arguments against using the MVSC as a MAV cabin it is tempting to conclude that it may be a design dead-end. However, there are alternate potential uses for a spacecraft such as this.

6.1 Crew Transfer Cabin

A potential emerging need is for a spacecraft to perform the role of crew transfer between co-located space vehicles. This has never been needed in human spaceflight; this is a level of space activity that has never been achieved (to date). Most flown crew-carrying spacecraft are small capsules. Only the United States, Russia/Soviet Union, and China have deployed space stations. There has never been a case where two complex spacecraft have been brought together – for instance if the International Space Station were to rendezvous and transfer crew with the no longer existent Mir space station. It would be a complex and potentially dangerous maneuver to bring these two vehicles together.

An ISS-Mir docking is purely a topic for fiction and analogy. However, this type of scenario could be possible in the future with one or more commercial Bigelow space stations, or with Mars Transfer Vehicles and CisLunar or other spacecraft. Even the ISS would have to make significant adjustments to receive a single Bigelow 330, let alone a large space vehicle composed of multiple BA-330 derived modules.

A Crew Transfer Vehicle (CTV) composed of the MVSC and a small service module (similar to the RCS sled developed by the MMSEV team) and possibly external manipulators for berthing operations could enable two large spacecraft to rendezvous to within some keep out zone, perhaps a few kilometers of each other. This distance would allow for a transfer of very short duration, on the order of minutes or hours, not days. Similar to the outfitting as a MAV, the CTV could accommodate up to four crew and 250 kg of cargo. Alternately, in a crew-only transfer the CTV could transfer up to six crew.

A longer duration CTV could install crew accommodations at the expense of crew capacity and accommodate two crew for a few days, perhaps a transfer between orbits or one with significant phasing. This CTV would replace two of the crew seats and the cargo section with a waste and hygiene system, galley, sleep provisions, and other crew supplies. The exact duration of such a vehicle could be defined in future sizing studies and mockup human in the loop evaluations. Test development should consider at least five days and perhaps not more than twenty days.

6.2 Crew Rescue Vehicle

A follow-on concept to that of the CTV is a Crew Rescue Vehicle (CRV). Such a vehicle would essentially be the orbital equivalent of an ambulance. Only useful for very short duration transfers, it could include space for two crew – one spacecraft operator and one medical caregiver – as well as a medical treatment area for one incapacitated crew member. Such a vehicle would shuttle back and forth to move injured crew to a location with more appropriate medical care. Again, the use case for such a spacecraft does not exist in today's space architectures, but in a future

6.3 Docking Tunnel

A stripped down minimal MAV cabin can also be used as a docking tunnel, providing a 134-inch connection between two elements. This could be useful both on a planetary surface and in microgravity.

6.3.1 Surface Applications

Surface applications for the docking tunnel are all related to the surface rover. A docking tunnel between a surface rover and the MAV cabin can as previously discussed allow for a MAV propulsion subsystem that is greater in diameter than the MAV cabin length. A docking tunnel between two rovers could provide additional crew volume during a dual rover excursion. Similarly, a single rover with a docking tunnel and logistics module could enable an extended surface rover mission. (Presumably the docking tunnel and logistics module would be carried by some other surface mobility asset.) Finally, a docking tunnel could provide an interface at the habitat for a surface rover docking. This might be needed to help clear obstacles such as habitat landing legs or power or thermal connection cables.

It should be noted that this docking tunnel is not ideal for connections between multiple habitat modules or between habitat and logistics modules. The reason for this is hatch size. The habitat is recommended to have a hatch height of at least 60 inches, where this cabin has a 40-inch hatch. The 60-inch height is important for routine, frequently repeated hatch traverses in the course of daily habitat operations. A smaller height would introduce numerous inefficiencies into crew operations.

6.3.2 Orbital Applications

In microgravity, this docking tunnel can serve as a generic connection between modules. The tunnel is larger than the volume needed for a pure pass-through, so there is limited volume inside these connecting modules for stowage, spacecraft subsystems equipment, or crew stations/workstations.

Additionally, the length of the module provides an inherent spacer between modules. This yields two potential advantages. The first is that the docking tunnel provides additional external surface area for mounting of exterior payloads or subsystems. Also, the docking tunnel separates modules that carry deployable appendages such as solar arrays and radiators. For instance, a docking tunnel between Orion and a Service Module enables space to reduce interference between Orion's solar arrays and those of the Service Module.

6.4 Extended Duration Repair Vehicle

The MVSC can also be used in conjunction with propulsion module of some kind and a proposed spacecraft called the Single Person Spacecraft (SPS) in order to conduct complex in-space repair operations. An extended duration repair vehicle (EDRV) such as this would not be an independent spacecraft, but could be deployed from a mother ship such as the International Space Station, Cislunar Habitat, or Mars Transfer Vehicle.

Similar to concepts that have been proposed since the 1950s [4], the SPS is currently under development by Genesis Engineering Solutions in Lanham, MD. [5] The SPS is an alternative to a spacesuit, encapsulating a single crew member in an almost body-conformal spacecraft equipped with multiple manipulator arms. [5] The SPS is intended for exploration or spacecraft servicing tasks. [5] Because it operates at the same atmosphere as its host vehicle it can provide immediate access without requiring pre-breathe time. [5]

The SPS, shown in Figure 7, consists of a hemispherical canopy attached to an inner pressure vessel and outer micrometeroid orbital debris (MMOD) shield. A hatch beneath the operator provides docking to a host spacecraft and transfer between the two. [4]

Figure 7. Single Person Spacecraft

The MVSC contains two axial docking ports, either or both of which could be used to dock a SPS. This configuration can overcome a key limitation of the SPS – mission endurance. The SPS is only intended to support a crew member for durations similar to a traditional Extravehicular Activity (EVA). However, complex repair tasks could potentially take days, or require significant tool swap outs. One or two SPSs can use a minimum MAV cabin as a base of operations.

For such a purpose the MVSC interior would be reconfigured to some extent. The cabin would be outfitted with crew systems such as a galley, sleep station(s), and waste and hygiene compartment, enabling multi-day use. The seats would not be needed and would be eliminated. A segment of the cabin could also be configured with polyethylene bricks as a radiation shelter for protection from solar particle events. Also, a tools and orbital replacement units (ORU) stowage bay in the cabin could allow for reconfiguration of the SPS during different repair tasks.

7 Conclusions / Recommendations

7.1 Subsystems Design Detail

The current concept for the MVSC assumes that the vehicle subsystems can either be mounted externally or be mounted on the interior surfaces of the cabin. An important next step will be to obtain the Master Equipment List (MEL) for the short duration MAV and attempt to place all of the subsystems in a CAD model of the MAV. Until this is complete, it will not be clear that the MVSC is large enough to accommodate the spacecraft's subsystems.

7.2 Design and Mockup Fabrication

After completing any revisions imposed by subsystems placement, the minimal MAV design can be used to develop a design for a medium fidelity mockup and then fabricate the vehicle. This work is expected to be completed by Habitability Design Center summer interns.

Preliminary intern studies have traded between a cylindrical skeletal core, shown in Figure 8, and a rectangular skeletal core, shown in Figure 9.

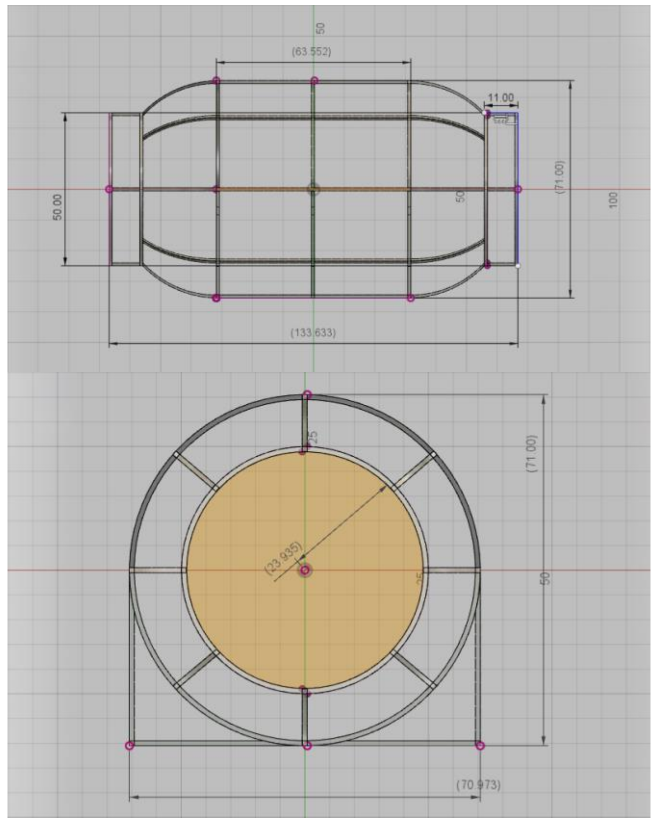

Figure 8. Cylindrical Skeletal Core Concept

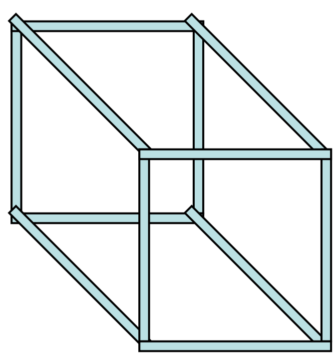

Figure 9. Rectangular Skeletal Core

In either case, the current expectation is that the mockup will use a skeletal frame of either 8020 or aluminum or steel bars. This skeleton will carry the mockup loads.

The mockup will be fabricated inside the NASA Habitability Design Center Lab, which presents a challenge. The lab currently lacks garage or high bay doors, with the only entry/exit via single and double doors, with a maximum exit width of 67 inches. But the MVSC is 73 inches wide. The mockup will definitely be tested in other buildings at JSC, which means it must be able to fit through the exit. Consequently, the sides must be designed to be removed from the mockup during transport. This may be more readily achieved with the rectangular skeletal core than with the cylindrical skeletal core. In either event, mockup completion is to be completed by the end of September 2016.

7.3 Human in the Loop Testing

Once the mockup is complete it can be used in ongoing NASA human in the loop tests. An initial test can evaluate the MVSC in its nominal mission, as a minimal MAV mockup to demonstrate crew transfer to/from a MMSEV mockup. This can assess the concept of shirt-sleeve crew transfer to the ascent vehicle, something anticipated in current EMC concepts.

Follow-on tests (if desired) can evaluate its use in other missions proposed in this paper. However, it can also be used to support testing of other habitats and capsules by providing an enclosed environment for transfer of crew between separated mockups.

Finally, the mockup can be used not so much in tests of itself but to support human in the loop testing of other mockups in multi-module tests. There are a number of habitat, cabin, and rover mockups at NASA Johnson Space Center, many of which are housed in different buildings. In particular, buildings 7, 9, 14, 29, 36, and 220 either house mockups or are targeted for new mockup construction. Some mission simulations could require the crew to transfer between buildings – for instance from the Orion mockup in Building 9 to the Human Exploration Research Analog in Building 220, to the (future) HESTIA mockup in Building 7. Normally, it would damage the isolation and confinement aspect of an analog mission to have crew move from building to building. However, the minimal MAV mockup could dock to the relevant mockup in each building to take on the crew, then be wheeled across the center to dock to another mockup, thereby transferring the crew, keeping the crew in an uninterrupted mission simulation environment.

Acknowledgment

The author would like to thank all current, former, and future members of NASA exploration project teams. Special thanks goes to the Evolvable Mars Campaign and the MMSEV project team.

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