A Safe Haven Concept for the Common Habitat in Moon, Mars, and Transit Environments

Robert L. Howard, Jr.[1]
NASA Johnson Space Center, Houston, TX, 77058, United States of America

The safe haven for the Common Habitat architectures, both the Deep Space Exploration Vehicle and the Moon/Mars surface basecamps, consists of the airlock, logistics modules, and in-space or surface pressurized rovers. These elements are repositioned to dock together and form a secondary habitable environment. The multiple elements that compose the safe haven and its ability to share utilities across docking ports give it multiple subsystem options to sustain the crew. In the safe haven configuration, the two logistics modules dock to the side hatches of the airlock outer chamber, one pressurized rover docks to the outermost airlock hatch, and the second pressurized rover docks to the first. This configuration provides no less than thirty days of habitation for the eight-person crew. It also allows the airlock inner chamber to be used for EVAs to both the exterior surface and the Common Habitat interior, which may have lost pressure during the event that triggered the need for a safe haven. These EVAs enable the crew to work to repair the habitat and restore habitation capability.

I. Nomenclature

ATHLETE = All-Terrain Hex-Limbed Extra-Terrestrial Explorer
DSEV = Deep Space Exploration Vehicle
ECLS = Environmental Control and Life Support
EMU = Extravehicular Mobility Unit
ISRU = In-Situ Resource Utilization
LEO = Low Earth Orbit
LSMS = Lightweight Surface Manipulator System
MGAAMA = Multi-Gravity Active-Active Mating Adapter
MMOD = Micrometeoroid and Orbital Debris
PPE = Personal Protective Equipment
PR = Pressurized Rover
PRISM = Pressurized Rover for In-Space Missions
RCS = Reaction Control System
RMS = Remote Manipulator System
SPE = Solar Particle Event
TCAN = Two-Chamber Airlock Node

II. Introduction

A safe haven provides additional options to both protect the health of the crew and increase the survivability of exploration spacecraft for deep space missions. It is essentially a secondary habitable environment that can sustain the crew should the primary habitable environment become incapable of supporting life.

Low Earth orbit (LEO) missions have been able to avoid the need for safe havens by employing redundancy management, reliability, and sparing strategies to reduce the likelihood of any serious failures, and escape capsules capable of returning the crew to Earth within hours of any unmanageable contingency.

[1] Habitability Domain Lead, Human Systems Engineering and Integration Division, AIAA Senior Member.

A large-diameter habitat that uses the SLS Core Stage Liquid Oxygen tank as the primary structure (similar to Skylab), the Common Habitat has an internal architecture compatible with microgravity, lunar gravity, and Mars gravity, such that identical versions of the same design can be used in all three environments. This large volume does not contain internal pressure bulkheads and therefore a safe haven solution is needed to enable this habitat to be used in missions beyond LEO.

III. Background and Context

A. Safe Haven Definition

For purposes of this paper, a safe haven is defined as an isolatable, habitable volume that a crew can retreat to when other habitable volumes have been rendered uninhabitable, thus enabling the crew to survive an incident that would have otherwise resulted in loss of crew. The Common Habitat architecture is a multi-destination human spaceflight architecture that uses the Common Habitat [1] as the primary habitation element on the Moon, on Mars, and in deep space. It is the core element of Moon and Mars surface basecamp pressurized elements, [2] shown in Fig. 1, and of the Deep Space Exploration Vehicle (DSEV), [3] shown in Fig. 2.

Due to the commonality aspect of the Common Habitat architecture, the safe haven concept in this paper applies to both the basecamps and the DSEV. It should be noted that the basecamp and the DSEV contain many of the same pressurized elements. In one area there is a noticeable difference. The surface basecamp includes two Pressurized Rovers (PRs). [2] These rovers are modified for use in the DSEV and are Pressurized Rovers for In-Space Missions (PRISM). [3] There is a significant difference between the PR and the PRISM as the PR is a wheeled mobility platform and the PRISM is a spacecraft with reaction control system (RCS) thrusters and a service module with a main engine. However, the PR and PRISM are the same type of element– small mobility elements that can separate from the main habitation system and operate independently. With respect to the safe haven, the PR and the PRISM bring the same capabilities to enable the safe haven.

(It is an unfortunate consequence of the acronym PRISM that it is both singular and plural. With the respect to the PR, two Pressurized Rovers is indicated as PRs, but two Pressurized Rovers for In-Space Missions are still two PRISM. PRsISM would be far too awkward to attempt to use. Instead, context must be used to understand how many PRISM are present when referenced.)

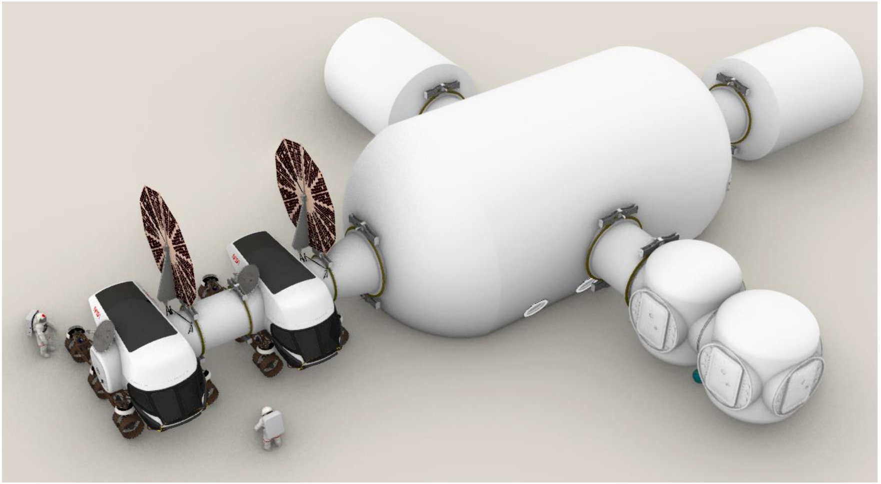

Fig. 1 Moon and Mars Surface Basecamp Pressurized Elements

For quick reference, in Fig. 1, the Two-Chamber Airlock Node (TCAN) is docked to the starboard docking port. One Logistics Module is docked to the port docking port and the other is docked to the forward docking port. The two PRs are docked to each other and to the aft docking port.

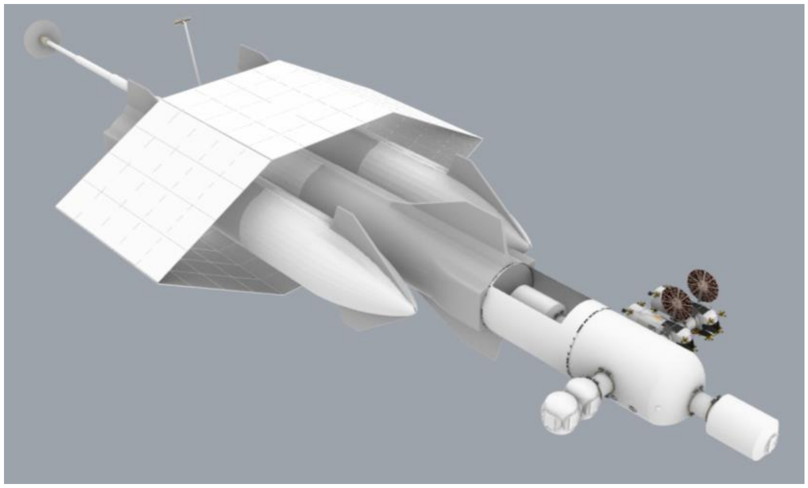

Fig. 2 Deep Space Exploration Vehicle

As shown in Fig. 2, the TCAN is docked to the DSEV starboard docking port and one Logistics Module is docked to the forward docking port – the same places they are docked to the Common Habitat in the basecamp. However, the second Logistics Module is docked to the aft docking port and the two PRISM are docked to the port docking port and to each other.

The crew will live in the safe haven until the impacted element can once again support crew. In the context of the Common Habitat architecture, abort options are limited, and, in some instances, there may be no abort options at all. This implies two design paths for the safe haven: either the safe haven must have the ability to sustain the crew for the remainder of the mission (allowing the crew to sacrifice the lost element), or the safe haven must support not only habitation but also repair. This latter case may involve EMU-suited or PPE-equipped crew excursions to the Common Habitat interior, or exterior EVAs to effect repairs.

B. Need for Safe Haven on Surfaces and in Space

Safe havens are often recommended for deep space missions including lunar and Martian surfaces. Orbital mechanics constraints limit crew return opportunities and even when a surface abort to an orbiting asset is available, it is not necessarily preferable over remaining on the surface due to possible extended orbital periods awaiting departure opportunities (yielding increased radiation and microgravity exposure), loss of surface mission objectives, and psychological consequences of an early surface departure.

Unless a mission infrastructure includes an unused complete duplicate habitation system the disabled habitat system must be recovered within a finite period of time. The services within the disabled habitat in most cases are still needed by the crew. Consequently, the safe haven must not only enable habitation but also recovery of the failed habitation system.

C. Causes for Safe Haven

The ISS Caution and Warning System has a tiered approach to alert the onboard crew and Mission Control in the event of off-nominal situations. The highest alert is an Emergency, or Class 1. An emergency is, “used to indicate a life-threatening condition that requires all crew to react immediately. This includes fire, rapid cabin depressurization or toxic release.” [4] Any of these would justify moving the crew into a safe haven. Additional emergencies include hazardous particulates in air or deposited on surfaces and cabin temperature outside of permissible ranges. Such an emergency that cannot be resolved in sufficient time will render the habitat uninhabitable, requiring the use of a safe haven. Several types of subsystem failures can also lead to emergencies.

The Common Habitat architecture is based on a multi-megawatt nuclear fission power system, for which the Common Habitat is one of several users. This assessment will not address the “loss of power generation” scenario as that falls within the scope of power system development and outside the scope of safe haven. It will consider “loss of power reception” and power management and distribution failures. These power failures can lead to an emergency because if the habitat cannot power the other subsystems it will be unable to sustain life.

Loss of atmosphere control means that the habitat can no longer supply oxygen or nitrogen, maintain air temperature or humidity, or remove carbon dioxide or toxins. The larger the habitat the longer control can be lost before harmful effects are observed, but eventually a habitat with such a failure will be unable to sustain life, resulting in an emergency. Loss of heat collection and transport will prevent the habitat from removing waste heat from onboard equipment. This will result in vehicle power downs to avoid damaging equipment through overheating, thereby creating the previously mentioned loss of power distribution, triggering an emergency. Loss of onboard processing and networking will render the habitat unable to control any of its subsystems, leading to many of the previously discussed failures and thereby making the habitat unable to sustain life, triggering an emergency. Any other subsystem failures that result in loss of habitability would also trigger a safe haven activation.

Solar particle events (SPEs) are not considered a cause for safe haven. Because an SPE is unrelated to vehicle condition, an SPE can occur at any point in time with no correlation with whether a safe haven is active or not. Thus, there is a need for an SPE shelter in both nominal habitat and safe haven configuration but an SPE does not trigger a safe haven activation. Instead, an SPE triggers a SPE shelter response (which may be different for different elements, different configurations of multi-element spacecraft, and/or different for different internal configurations of a given element). For instance, the pressurized rovers incorporate a water-based heat sink on the cabin roof and stowage on the walls, forming a natural SPE shelter inherent to the vehicle's nominal configuration. Other spacecraft may choose to "build a fort" as an SPE shelter, rearranging internal stowage to form the type of barrier that is already inherent to the rover's design.

D. Limitations of Safe Haven

However, a safe haven does not protect against all possible failures and may have other limitations. For instance, a complete loss of water supply will render the crew without potable water. No amount of time in a safe haven will allow the crew to regain lost water. In an in-situ resource utilization (ISRU) architecture with water production it is possible that water can be extracted from local sources to replace the water that was lost, but the presence or absence of a safe haven does not contribute to this recovery. Additionally, a safe haven is limited in terms of the duration for which it can provide protection or the level of functionality it affords the crew. Unless it is a complete duplicate of the original spacecraft (e.g. a redundant basecamp or a redundant DSEV), it does not contain the full functionality of the pre-emergency system. Thus, a safe haven may carry a limited amount of logistics, or inferior habitation systems, or inferior mission systems, etc. Generally (except for the case of a duplicate spacecraft), a safe haven is a temporary solution that may not be sufficient to complete the original mission.

IV. Common Habitat Architecture Safe Haven Elements

While it is the primary focus of this paper, the need for a safe haven does not apply only to impacts to the primary habitat. Loss of habitation capability can happen to any habitable element. Safe haven must therefore consider how the loss of any given habitable element will impact the crew and how to recover from such a loss.

The Common Habitat is the core of a safe haven for failure in any other pressurized element in the architecture. Should any such element lose its ability to sustain the crew, it can be isolated while the crew uses the nominal capabilities of the Common Habitat and the remaining elements to repair any damage and restore the affected element.

Most failures that trigger a safe haven are not instantaneous and will carry a certain window of time to react. This will allow the crew to take actions to preserve as much functionality as possible. There are correspondingly implications for each element.

There are also a few design impacts for logistics. There needs to be a way to quickly unload stowage from a Logistics Module that is losing habitation capability. This impacts the design of stowage secondary structure – quick releases can enable moving of large clusters of stowage at once (e.g. moving 50 CTBs at a time or more). It may also be reasonable to carry two Logistics Modules on missions that only require one. This provides additional redundancy and can simplify resupply and trash operations should one module be rendered unusable. The conditions necessitating safe haven use for a failed Logistics Module also underscore the need for logistics management capabilities that allow *rapid prioritization, identification and localization of contents to be moved.

The windows of both the PR and the PRISM may be perceived as a micrometeoroid and orbital debris (MMOD) impact risk. It may be an option to consider removable or deployable MMOD shutters or shields that can cover their windows when docked to the Common Habitat.

There will be a need to rapidly evacuate suits (and possibly stowage) in event of a Two-Chamber Airlock Node (TCAN) [5] loss of habitation capability. The suits and stowage can be evacuated to the other chamber (if only one chamber is lost), the Common Habitat, or the PRISM. EVAs from the PR/PRISM can be used to recover the suits and/or stowage if the TCAN chamber depressurized before these transfers could be made. The following steps would be required:

- Dock PR/PRISM to damaged chamber but do not open hatches

- Conduct an EVA from suitports to the damaged TCAN chamber exterior (using an undocked hatch for ingress)
- Ingress damaged chamber
- Depressurize PR/PRISM cabin
- Recover suits from TCAN
- Open hatch to now-depressurized PR/PRISM
- Transfer suits to PR/PRISM
- Close PR/PRISM hatch from within TCAN
- Repressurize PR/PRISM
- Egress TCAN and return to PR/PRISM suitports
- Ingress PR/PRISM once pressurized
- Pilot PR/PRISM to available Common Habitat docking port
- Conduct suit inspections and repair in Common Habitat maintenance work area

After the initial recovery, the failed Logistics Module, PR/PRISM, or TCAN are treated just like a failure of any other external element to be repaired by the Common Habitat.

In addition to considerations for each element, safe haven requirements extend to the vehicle as a whole and the physical interfaces among elements. An immediately apparent implication is that it may be wise to implement motorized doors across the architecture, protecting against several typical causes for safe haven such as loss of pressure, fire, or toxic atmosphere. Any loss of pressure due to a debris strike can be minimized by remotely isolating the impacted volume and a fire or toxic release can be contained from spreading. Future flight rules could determine whether this is an automated, crew commanded, or ground commanded capability and what criteria are involved in issuing isolation commands. All such motorized doors should have a manual override capability.

The remainder of this paper focuses on the safe haven response in the event of a Common Habitat failure. The safe haven for failures in the Common Habitat is a secondary habitable zone docked to the Common Habitat. All eight crew live within the safe haven while the habitat is recovered. The elements that form this zone include one Two-Chamber Node Airlock, two Logistics Modules, and two Pressurized Rovers. This combination of modules provides flexible safe haven capability. The Logistics Modules already include most crew consumables, spares, and supplies, with 30-day supplies marked for easy identification. The rovers include limited waste management, meal preparation, exercise, hygiene, and medical capability. Both the rovers and TCAN provide EVA capability, including EVA into a depressurized Common Habitat interior. The TCAN further provides suit maintenance support. The TCAN, rovers, and Logistics Modules all provide open loop ECLSS capability.

V. Safe Haven Configuration

A. Safe Haven Subsystems

The Logistics Module, TCAN, and PR/PRISM all contain open-loop environmental control and life support (ECLS) subsystems. Collectively, they are sufficient for at least 30 days of operation.

In most safe haven scenarios, the Common Habitat water tanks are still viable and can provide water for the crew. If Common Habitat water is not available, each PRISM already carries sufficient water to sustain two crew for 30 days. The TCAN and/or Logistics Modules must also provide sufficient water stowage to sustain a total of four crew for 30 days.

A significant amount of redundancy is built into the logistics supplies for safe haven. 68.75 CTBE is allocated for 30 days supplies for eight crew. Each logistics module includes a 30-day 68.75 CTBE stowage allocation in emergency CTBs. A portion of the mission consumables is reserved for safe haven use and permanently stowed in each Logistics Module. This avoids reliance on PR/PRISM consumables and ensures that a 30-day supply is available even if the Safe Have is triggered just as both PR/PRISM are returning from an excursion and are low on supplies. It further offers redundancy in the event one logistics module is lost, or a 60-day supply if both are available. Of course, all of the additional nominal logistics are also within the Logistics Modules. Logistics in the Common Habitat may be also retrievable depending on nature of safe haven emergency. The Emergency CTBs in each Logistics Module are a different color from the others to prevent accidental removal. Emergency CTB supplies may be consumed by the crew during the final 60 days of a mission if not previously needed.

Safe havens can also be activated (with lesser degrees of capability) from individual elements without docking together: PR/PRISM alone, PR/PRISM + TCAN, Logistics Module alone, Logistics Module + TCAN, etc.

Depending on the nature of the event that triggered safe haven, this configuration can draw water and potentially other operational utilities from the Common Habitat but is otherwise independent. The MGAAMA [6] design enables utility connections to operate across closed hatches, but even with no operational utilities from the Common Habitat, the safe haven can sustain the crew for at least 30 days.

If primary power is uninterrupted, the safe haven can continue to receive power from the nuclear fission reactor. If primary power is unavailable, the safe haven can receive power from the PR/PRISM solar arrays and batteries. A forward work task may investigate additional secondary power sources.

If the Common Habitat's thermal control system is unaffected, thermal control can continue as nominal. If the Common Habitat thermal control system is nonfunctional, an external EVA can connect a bypass to an open docking port on the TCAN, Logistics Module, or PR/PRISM. Until this bypass is connected, the safe haven will operate in a low power mode using the PR/PRISM radiators and fusible heat sinks for cooling.

During safe haven operations, the PR/PRISM will provide communications and guidance, navigation, and control capability. The data network is already integrated and will simply exclude the Common Habitat if its network is unavailable.

B. Docked Configuration

Safe haven can be activated on any port on Common Habitat, though the TCAN is always the direct connection between the safe haven and Common Habitat. Port selection is an operational decision that can be made real-time or in accordance with established flight rules. In the case of the DSEV, the aft docking port cannot host the safe haven because there is insufficient clearance in the intertank to contain more than just a single docked logistics module. Thus, only the other three ports are available, and the default selection is the forward port as this offers the least disruption to vehicle c.g. In all cases, the TCAN inner chamber becomes the Crew Lock and the outer chamber becomes the Equipment Lock. This can be achieved either by reconfiguring the TCAN interior or by reorienting which hatch is docked to the Common Habitat. The Logistics Modules will dock to the two side ports on the TCAN outer chamber and the PR/PRISMs will dock to each other and to the TCAN outermost port. This configuration positions the PR/PRISM to dock and undock as needed, for instance, to serve as mobile EVA platforms to access various sections of the Common Habitat or other basecamp/DSEV elements. It also positions the Logistics Modules such that they do not block the TCAN inner chamber side hatches. The basecamp safe haven configuration is shown in Fig. 3 and the DSEV safe haven configuration is shown in Fig. 4. In both cases, the two Logistics Modules are docked to the side docking ports of the TCAN's outer chamber. The PR/PRISM are docked to the outermost docking port of the TCAN outer chamber. The TCAN itself can be docked to any Common Habitat docking port in the basecamp. For the DSEV it is typically docked to the habitat forward port but could be docked to the starboard or port docking ports should a reason dictate doing so.

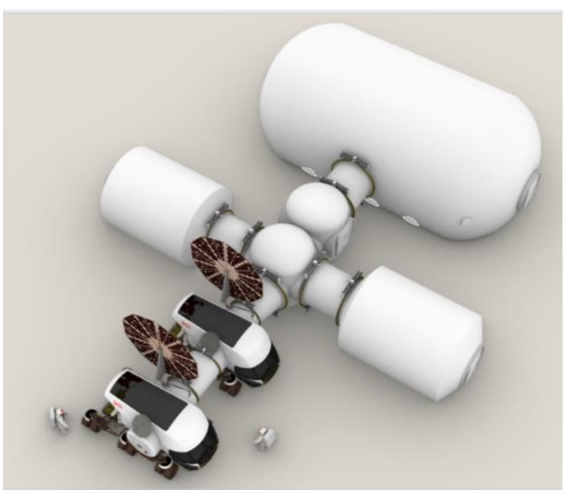

Fig. 3 Basecamp Safe Haven Configuration

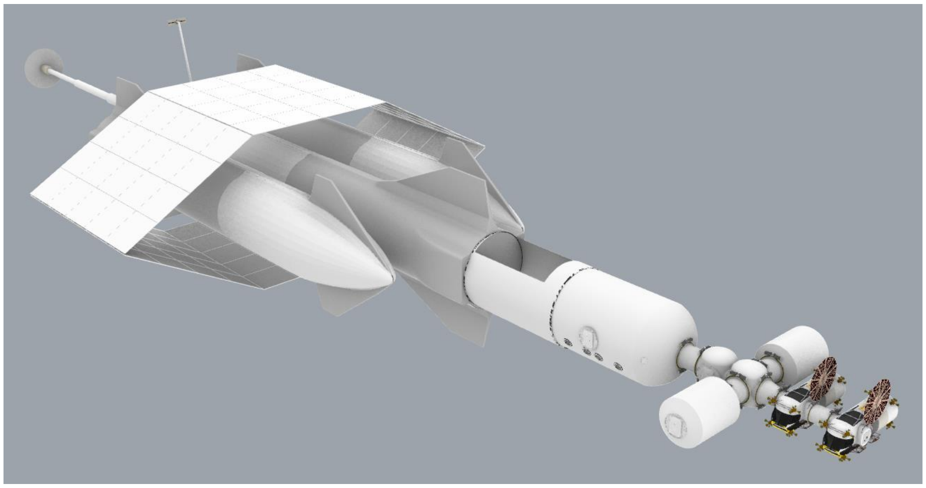

Fig. 4 Deep Space Exploration Vehicle safe haven Configuration

C. EVA Capability in Safe Haven

While in safe haven, the crew members can conduct EVAs to the external environment from three potential paths. The PR/PRISM suitports can be used to perform EVA from either PR/PRISM. Additionally, the TCAN can be used to perform external EVAs with crew ingress/egress through either side hatch of the inner chamber.

In the event that the Common Habitat has lost pressure, EVAs can be conducted to the Common Habitat interior by using the TCAN innermost hatch. This was the primary reason to reconfigure the TCAN to use the inner chamber as the crew lock.

VI. Transition from Nominal to safe haven Configuration

A. Robotics System Support

The use of robotic systems to support reconfiguration to safe haven requires a different approach in microgravity vs. gravity environments. Thus, one approach is used for the Moon and Mars basecamps and a different approach for the DSEV. (Note that in all docking/undocking operations described below, except where noted otherwise the associated MGAAMA is moved with its element.)

In both reconfigurations, the crew will nominally travel in the PR/PRISM, but it is theoretically possible for crew members to both reside in, and issue commands from the TCAN or Logistics Modules during reconfiguration. This off-nominal crew operation is necessary in split crew scenarios where a safe haven is triggered during a PR/PRISM excursion where neither PR/PRISM is present. The PR/PRISM would naturally be recalled in such a case, but the safe haven reconfiguration may need to be completed before either PR/PRISM can return. Considerations unique to the Deep Space Exploration Vehicle and Moon/Mars basecamp cases are detailed below.

1. Deep Space Exploration Vehicle

The robotic system used with the DSEV is the Remote Manipulator System (RMS). The most complex scenario is if the TCAN needs to be relocated to a different port. If the safe haven emergency occurs during a period where thrusting is required or anticipated, the forward docking port must be used to prevent the shift in center of gravity that would accompany use of the side ports. This will require moving the TCAN. If no thrusting is anticipated, the safe haven can use the TCAN's nominal side port location.

The PRISM will first undock from the Common Habitat. The joined PRISM formation: 4x6 multi-gravity active-active mating adapter (MGAAMA), PRISM, 4x4 MGAAMA, PRISM will move away to give the RMS uninterrupted volume to work.

The RMS will then undock the Logistics Module from the forward docking port. Using its ability to translate with a payload, the arm will move the Logistics Module to the vacated port docking port and temporarily place it there.

The RMS will next undock the TCAN from the starboard docking port and dock the crew lock to the forward docking port. This may involve first docking the TCAN/MGAAMA to the docking port, then undocking the TCAN from the MGAAMA, rotating the TCAN 180 degrees to change port assignments, then docking the crew lock outermost port to the MGAAMA. (Thus, the crew lock is docked to the Common Habitat and the equipment lock is now the outer chamber.) Alternately, the RMS may simply dock the TCAN/MGAAMA to the docking port, leaving it as a crew action to reconfigure the TCAN chambers.

The RMS will undock the Logistics Module 1 from the port docking port and dock it to the TCAN outer chamber port docking port. The RMS will undock the Logistics Module 2 from the aft docking port and dock it to the TCAN outer chamber starboard docking port. The PRISM stack will dock to the TCAN outer chamber forward docking port, completing the safe haven configuration.

2. Moon/Mars Basecamp

The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robots [7] are the primary robotic system used with the surface basecamps. Mars gravity makes lifting the Logistics Modules particularly challenging if full. Consequently, a towing solution offers potential advantages and has corresponding design impacts for the support cradles of both the Logistics Modules and TCAN, as well as for a 3D printed surface immediately surrounding the basecamp pressurized elements.

As part of the nominal basecamp construction, it was assumed that a trench would be dug to emplace the Common Habitat and that the surface of the trench be either sintered or 3D printed to provide a more stable base than simply regolith. It was also assumed that a 60-meter diameter, load bearing surface would be required surrounding the Common Habitat. Safe haven and logistics operations (both requiring the moving of 30-ton Logistics Modules) suggest that this surface may need to be 3D printed.

Additionally, the leveling legs/support stands for the TCAN and Logistics Modules must have steerable wheels (whether retractable or locking, whether commanded or freely swiveling) and there must be an interface on either the modules themselves or on their leveling legs/support stands that ATHLETEs can grapple.

While the TCAN can be moved to position the safe haven at a different port, there is generally no need to do so (unless the triggering event had also damaged a needed portion of the local surface).

As an operational trade (likely a trade of crew time versus ATHLETE speed) will reconfigure the TCAN either through means of the crew internally swapping the crew lock and equipment lock with the inner and outer chambers, or through means of an ATHLETE towing the TCAN to swap which chamber is connected to the MGAAMA and therefore docked to the Common Habitat.

ATHLETEs will tow the Logistics Modules from their current ports to dock them with the TCAN outer chamber side docking ports. Because there are multiple ATHLETEs on the surface, all of the ATHLETE-towed operations can occur in parallel.

The PRs will undock from each other and the Common Habitat. They will drive to the TCAN and redock, first to the TCAN outer port and then to each other, completing the reconfiguration to safe haven.

Lightweight Surface Manipulator System (LSMS) [8] cranes may also be considered to do some of what is described here as performed by the ATHLETEs for surface basecamp reconfiguration. Future trades are envisioned to address these functions at an architectural level.

B. Crew Activity

Crew activity during safe haven reconfiguration will vary slightly depending on whether the two PR/PRISM are present or absent. The general operation is the same for both the basecamp and the DSEV.

1. PR/PRISM Present

Upon declaration of safe haven, if there is sufficient time the crew will transfer environmentally uncontrolled logistics not needed for safe haven from Logistics Modules to the Common Habitat. This includes items that do not require environmental conditioning and could survive in a depressurized habitat. This action creates additional habitable volume in Logistics Modules. The crew will then close TCAN and Logistics Module hatches. The crew will ingress the PR/PRISM, close hatches, and undock. The PR/PRISM will move to a location out of the way of the reconfiguration that also provides the crew with a clear view of robotic activity.

Crew presence in the PR/PRISM can vary. Typically, half the crew will enter each PR/PRISM. But it is possible for one PR/PRISM to be teleoperated from the other, so there is no requirement for crew distribution. Also, the PRs will typically (but not necessarily always) undock from each other and drive as independent vehicles. The PRISM can do the same or they can fly in a docked configuration. Also, normally the PR/PRISM are used together, thus if one is present the other most likely is as well. But it is possible that in some cases only a single PR/PRISM may be present.

The TCAN is first relocated if necessary, as previously described. Next, the Logistics Modules are relocated, also as previously described. It is worth noting that a case could be made for only relocating one Logistics Module. If the modules had been loaded such that one module included raw materials needed for habitat repair it might under some circumstances be preferable to leave that module docked to the Common Habitat such that it could be depressurized and accessed by crew performing repair operations.

The crew will then dock both PR/PRISM to each other and to the TCAN outer chamber.

The crew will equalize the safe haven stack to 8.2 psi. Higher pressures may be acceptable if EVA is not anticipated, but the lower pressure may also enable oxygen consumables to last longer and may therefore be preferable. The crew will open hatches between PR/PRISM and the remainder of the safe haven stack (PR/PRISM + TCAN + Logistics Modules)

The crew will set up four temporary sleep restraints / cots in the Logistics Modules and/or TCAN equipment lock. Four crew will sleep in the two PR/PRISM while the other four sleep in Logistics Modules/TCAN.

2. PR/PRISM Absent

Upon declaration of safe haven, the Common Habitat crew will transmit declaration of safe haven to the PR/PRISM and request immediate return to the Common Habitat.

If there is sufficient time the crew will transfer environmentally uncontrolled logistics not needed for safe haven from Logistics Modules to the Common Habitat.

The crew will then close all Logistics Module hatches.

The crew will egress the Common Habitat into the TCAN and close the hatch. If necessary, they will then command relocation of the TCAN. In this scenario, the faster solution will likely be to use the robotic systems to reorient the TCAN rather than use the crew to reconfigure the interior.

With the TCAN at the proper docking port for safe haven, the crew will relocate the Logistics Modules to the TCAN outer chamber side docking ports.

They will then equalize the stack to 8.2 psi and open internal hatches across the TCAN and Logistics Module stack. They will next set up four temporary sleep restraints / cots in Logistics Modules and/or TCAN equipment lock. Temporary waste management and meal prep may be necessary and set up in one of the Logistics Modules until PR/PRISM return, which in the case of the most distant excursions could be up to 24 hours.

When the PR/PRISM return to the Common Habitat, both dock to the TCAN outermost docking port.

VII. Crew Habitation and Operations in Safe Haven

Because the crew can remain in safe haven for an extended period of time, the safe haven must be a habitable environment for eight crew. While it clearly will not be the same standard of living possible in the Common Habitat, it must not add stressors that could interfere with the crew's ability to recover the damaged habitat.

Each PR/PRISM already includes two bunks and those will be available to half of the crew. For the remaining crew, temporary sleep accommodations are necessary. As previously indicated, they can be set up in both of the Logistics Modules and the TCAN equipment lock, so there is a limited ability to spread out. While the temporary sleep accommodations are notional and require forward work, options include suspended hammocks, Army-style cots, and deployable visual privacy screens notionally comparable to small tents.

Each PR/PRISM also includes a waste management system commode. These two toilets will be used by the crew. As previously noted, a temporary toilet can also be set up in a Logistics Module. This might be a custom minimum functional unit, or it could be a flight spare to the standard toilet used in the PR/PRISM and Common Habitat. A deployable privacy screen of some type will be needed.

Hygiene capability is limited. The PR/PRISM uses the waste management volume as a private area where hygiene can be conducted but does not have the features available in the Common Habitat. Similarly, deployable privacy barriers can be set up in the Logistics Module to supplement the PR/PRISM volumes, thereby allowing more crew to conduct full body, oral, or facial hygiene in parallel.

Each PR/PRISM includes a potable water dispenser that can be used to provide drinking water and to rehydrate food and drink packets. Sharing this system across twice the intended number of crew may require the crew to eat meals in shifts instead of as a group.

Each PR/PRISM has sufficient stowage volume to include a fairly robust suite of medical supplies. While inferior to the Common Habitat, it can be outfitted with supplies roughly equivalent to the medical kits available aboard the International Space Station.

The PR/PRISM includes a combination resistive/aerobic exercise device that will help slow the rate of deconditioning while away from the Common Habitat's extensive exercise systems. Because there are eight crew and only two devices, they will be in use for a significant portion of each day.

The TCAN equipment lock is likely the best volume for in-person meetings of the entire crew. Depending on how full the Logistics Modules were at the time of safe haven initiation those may also provide options. Videoconferencing is also possible with four crew in each PR/PRISM.

It is entirely possible that a solar particle event (SPE) may occur during a safe haven event. Fortunately, the safe haven configuration offers multiple shelter locations. The PR/PRISM is inherently designed for SPE protection thanks to its fusible heat sink. Additionally, the stowage in the Logistics Modules also provide protection. While no analysis has yet been performed, the location of stowed PLSS and subsystems in the upper dome of the TCAN equipment lock and stowed suits in its lower dome, plus the elements docked to each docking port, it is likely that the equipment lock is also reasonably well protected during SPEs. Water tanks in the PR/PRISM and temporary water stowage in the Logistics Modules and/or TCAN also provide protection. Thus, the crew has credible options to respond to any SPE incidents that occur while in safe haven.

Clearly, the crew cannot simply live in the safe haven. Generally, active effort on the part of the crew will be necessary to recover from any incident that triggers use of the safe haven. While the disabled systems are likely to vary in different safe haven scenarios, there is a general order in which functionality will need to be restored. A first priority is to extinguish any active fires and control any potential sources of re-ignition or spread. At this point it will be possible for crew to enter the habitat, potentially with spacesuits/PPE. Once safed, the crew is clear to restore power reception and power management and distribution. With power available, other systems can be brought back online as they are repaired. This includes restoration of onboard processing and networking, thereby enabling commanding to vehicle subsystems. If the habitat is depressurized, the crew must restore the habitat's ability to pressurize. This will involve sealing any hull penetrations or repairing any seal leaks. Once the habitat can hold pressure, the crew can restore its ability to control cabin air temperature and humidity, control oxygen and nitrogen partial pressures, and remove carbon dioxide. At this point the crew can enter without spacesuits, potentially with personal protective equipment (PPE). The crew can then remediate any toxins or particulates in the air or on surfaces. Once complete, the crew enter with no protection. If not functional, the crew can now restore active thermal control including heat collection and transport. This will make it possible to end any vehicle power downs. At this point the crew can operate the Common Habitat, though there may be remaining subsystem and payload component damage that requires additional repair. In some cases, an initial repair will be performed to enable basic operating capability, with more extensive repairs performed at later stages to restore full functionality. It is worth noting that most of the fabrication, maintenance, and repair capability is located in the Common Habitat. It is at the center of the mid deck, placing it in one of the most protected locations in the architecture. However, the design of this area should consider resilience against the conditions that can cause safe haven to be triggered. It will also need to be consider whether some portions of the facility may need to be used by suited crew members or crew wearing PPE during the recovery process. Some equipment may also need to operate in vacuum, potentially those needed to support pressure vessel repairs.

While the first priority during a safe haven event (aside from reconfiguring to the safe haven configuration – thereby protecting the crew) is recovering the habitat from damage suffered, it is also important to minimize impact to mission objectives, including science operations and equipment. The first science-protecting opportunity is to minimize catastrophic damage to as many payloads as possible. Some payloads, particularly live biological payloads, are at particular risk. Cold storage may also be at risk. Some of these may be able to be saved during the safe haven reconfiguration activity or via post-reconfiguration EVAs to the laboratory work spaces. Second, some payloads remaining in the Common Habitat may be able to operate in an untended capacity. However untended operations may still require initial configuration, activation, and adjustments necessitating EVA activity to the Common Habitat laboratory spaces. Opportunistic science will also arise to study the impact of the safe haven event on the spacecraft as well as on the crew, both physically and psychologically. Finally, some PR/PRISM-based scientific research may be able to continue. Undocking for separated ops during a safe haven event will be a scenario-specific decision Mission Control will have to assess, but because the rovers still have the ability to operate independently, they can be used in cases where the risk is deemed acceptable.

VIII. Conclusion

The safe haven configuration dramatically increases the survivability of both the surface basecamp and DSEV spacecraft. The versatility and robustness of the constituent spacecraft put the crew not only in a position to survive, but also to recover and continue the mission. Given that a disabled habitat cannot be used by subsequent crews unless it is repaired, the ability of the safe haven to support crew recovery and repair activity is especially significant. The safe haven presented in this paper is not a lifeboat where crew will huddle with diminishing hopes. It is instead a highly functional subset of the architecture where once activated, the safe haven provides facilities and logistics to support the envisioned 8 crew for at least 30 days, enabling habitation and operational performance functions (e.g., crew sleep, waste management, hygiene, meal preparation and consumption, medical care, exercise, EVA, spacesuit repair, and crew meetings). While in the safe haven configuration, the crew has access to most of the basecamp or DSEV's logistics. EVA crew can venture from the safe haven onto or into the damaged spacecraft to conduct repairs and other activities to restore habitat functionality. When not needed to support those activities, non-EVA crew can continue other pressurized operations within the safe haven, including limited forms of scientific research and even conducting detached Pressurized Rover operations if needed.

Forward work includes investigation of additional power sources and energy storage for the Common Habitat architecture, including both external means of power generation and potential locations for batteries or other energy storage systems inside the habitat. Forward work also includes an assessment of options for surface transportation of elements in the immediate vicinity of the habitat. This includes options to use LSMS cranes to assist with docking or undocking of elements from the Common Habitat and relocating them to alternate docking ports. Another element of forward work concerns the interior configuration of the TCAN and Logistics Modules during safe haven operations. This includes design of the temporary sleep accommodations, locations for temporary waste management and hygiene, and considerations for crew meetings.

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