A Common Habitat Deep Space Exploration Vehicle for Transit and Orbital Operations

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When outfitted as a habitat, the SLS Core Stage Liquid Oxygen Tank is a pressure vessel that can be used to support human exploration in deep space. An exploration spacecraft can be constructed with this habitat, known as the Common Habitat, as its central element. More than just a transit vehicle, this spacecraft is a Deep Space Exploration Vehicle – a microgravity science laboratory capable of conducting research with onboard human crews throughout the inner solar system. Supplied with propellant by LEO depots, preliminary trajectory and Δv estimates indicate that the spacecraft can perform fly-by or orbital missions with trajectories close enough to the sun to intersect the orbit of Mercury or far enough away to fly by the main belt asteroid Vesta. Its primary mission, however, is to support human expeditions to Mars. Many, though not all, of the pressurized and unpressurized elements that compose the Deep Space Exploration Vehicle can also be used in surface base camps on the Moon and Mars. In additional to traditional space science disciplines, the spacecraft offers unique potential for small asteroid retrieval and for artificial gravity research. Three launches are used to deploy the spacecraft, but thirty-nine launches are used to deliver propellant to orbit to fully fuel the spacecraft for deep space missions. Key operations in a Mars crewed mission are described to illustrate how the vehicle is used and forward work is listed to mature the spacecraft concept.

I. Nomenclature

ARED = Advanced Resistive Exercise Device
ATB = Ames Trajectory Browser
CEVIS = Cycle Ergometer with Vibration Isolation System
CH_4 = Methane
CTB = Cargo Transfer Bag
DSEV = Deep Space Exploration Vehicle
DST = Deep Space Transport
EVA = Extravehicular Activity
HAVOC = High Altitude Venus Operational Concept
HEO = High Earth Orbit
JUMP = Joinable Undercarriage to Maximize Payload
LEO = Low Earth Orbit
LM = Logistics Module
LOX = Liquid Oxygen
MDL = Mid Deck Locker
MGAAMA = Multi-Gravity Active-Active Mating Adapter
MMSEV = Multi-Mission Space Exploration Vehicle
MTV = Mars Transit Vehicle
NEA = Near-Earth Asteroid
NEP = Nuclear Electric Propulsion
PR = Pressurized Rover
PRISM = Pressurized Rover for In-Space Missions
RMS = Remote Manipulator System

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SAFER = Simplified Aid For EVA Rescue
SLS = Space Launch System
SPS = Single Person Spacecraft
T2 = 2nd Generation TVIS (Treadmill with Vibration Isolation System)
TCAN = Two-Chamber Airlock Node

II. Introduction

The Common Habitat is the conceptual central element of a human spaceflight architecture signified by a long-duration habitat designed to be equally suitable for human use in different gravity environments: 0g, 1/6g, 3/8g, 1g, and artificial gravity. [1] The Common Habitat is not part of the current NASA reference architectures for exploration of the Moon and Mars. It is instead an ongoing study of potential options that – should viability be demonstrated – could potentially be applied to human exploration programs. It shares a similar design approach to Skylab in that it uses the SLS Core Stage Liquid Oxygen (LOX) tank as the primary structure and pressure vessel. The hope is that Common Habitat studies will identify systems, architectures, and elements with potential to significantly advance NASA human space exploration if merged with NASA plans.

Shown in Fig. 1, the Common Habitat is 8.41 meters in diameter and 15 meters in length, providing living and working space for an eight-person crew. It includes four docking ports, one at each longitudinal end and two radial docking ports midships. Each docking port includes a 40-inch wide by 60-inch tall hatch and is compatible with the 6x6 and related Multi-Gravity Active-Active Mating Adapter (MGAAMA) docking systems. [2]

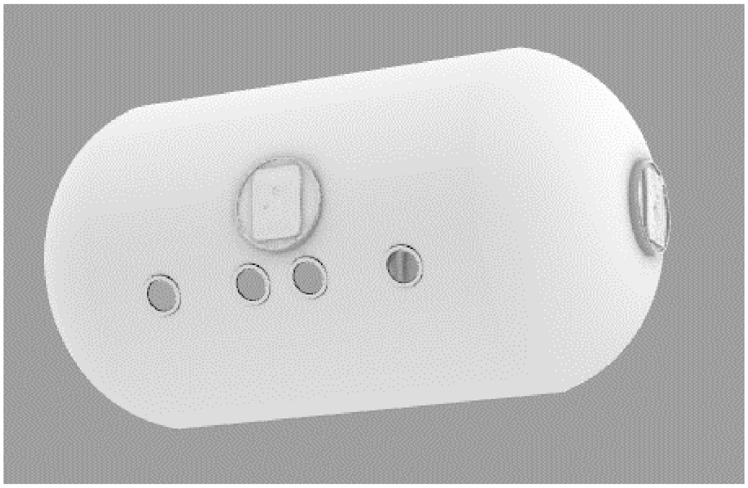

Fig. 1 Common Habitat

The Upper Deck, shown in Fig. 2, is the primary social and group operations volume of the habitat. It includes a galley with plant growth chambers, reconfigurable wardroom, panoramic projection screen, hygeine compartment, medical care facility, command and control center, and subsystems equipment.

Fig. 2 Common Habitat Upper Deck

The Mid Deck, shown in Fig. 3, is the primary working volume of the habitat. It includes an extensive exercise countermeasures facility with ISS-compatible exercise equipment (ARED, CEVIS, and T2), a fabrication, maintenance, and repair facility, a life sciences laboratory including both space biology and human research, and a physical science laboratory including geology, remote sensing, and physics.

Fig. 3 Common Habitat Mid Deck

The Lower Deck, shown in Fig. 4, is the private volume of the habitat. It includes eight identical, private crew quarters, each with room for a horizontal bunk, personal work desk, limited floor space, and 10.5 mid deck locker equivalent stowage volume. The deck also includes four combined hygiene and waste management facilities. Each includes a private waste management compartment, private full body hygiene compartment, and a clothes changing/personal items stowage chamber that serves as the outer room to both hygiene and waste management.

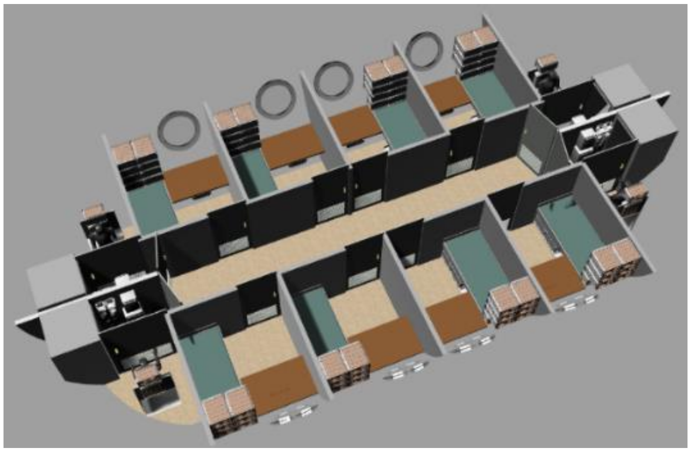

Fig. 4 Common Habitat Lower Deck

This paper describes how the Common Habitat can be applied to the in-space habitation role, developing a spacecraft around it that is used, among other things, in support of human missions to Mars. It effectively creates the in-space leg of a broader, Common Habitat enabled human exploration architecture. Given the baseline philosophy of the Common Habitat to use the same habitat design for surface and microgravity habitation it becomes an obvious question to determine what a transit spacecraft looks like if the Common Habitat is its habitation element.

This architecture was created specifically to apply to the Common Habitat and has no existence beyond the Common Habitat study. Where it makes use of existing spacecraft or spacecraft from other development studies it makes no commitment to remain consistent with the current designs of those elements and no programmatic intent is implied by any such divergences.

III. Background and Context

Many of the historic Mars architectures used the term Mars Transfer Vehicle (MTV) to describe the habitable spacecraft used by astronaut crews between Earth orbit and Mars orbit. Since the cancellation of the Constellation program, the term Deep Space Transport (DST) has gained in popularity for a spacecraft fulfilling the same role. (The DST envisioned immediately after the cancellation of Constellation was initially intended for human missions to a Near-Earth Asteroid instead of Mars, but later use of the DST in concept studies focused on Mars.) This architecture intentionally uses the name Deep Space Exploration Vehicle (DSEV) instead of MTV or DST to indicate a level of capability enabled in this spacecraft that did not exist in historic MTV and DST concepts.

Using the word "Mars" in the MTV name of a spacecraft is also not considered appropriate for the DSEV because while it does travel to Mars, it is intended for missions to more destinations than only those involving Mars. Words like Transport or Transfer are not considered adequately descriptive for the DSEV because those words imply that the mission begins at the destination – the transit or transportation is essentially the necessary evil to get to the mission.

By comparison, "Deep Space" has historically been used to encompass to more than a single location in space beyond Low Earth Orbit. This is consistent with the intended range of the DSEV, which primarily operates in the inner solar system. "Exploration Vehicle" implies that the mission is continuous; transit is as much the mission as is the destination. An MTV might be perceived as transporting the crew to Mars, with the actual exploration taking place on the Martian surface. The DSEV differs in that it is a mobile exploration facility that conducts exploration of the solar system and also dispatches crewed expeditions to bodies of interest, which can include the surfaces of asteroids, moons, and planets.

When operating in support of Mars surface crew missions, the DSEV departs from and returns to LEO. While the DSEV is capable of operating in LEO, it primarily travels beyond LEO. It is capable of very long transit cruises and remains in Mars orbit uncrewed while the crew is on the surface. Its primary exploration focus is Mars and Earth-Mars trajectories, but this research will show it is also capable of operations in other destinations.

Where possible, the DSEV is intended to share common elements with the surface base camps. This reduces development expense, simplifies crew training, strengthens partnering and acquisition strategies, and improves reliability knowledge for components. Individual elements and their respective commonality will be discussed later in this paper.

IV. Deep Space Exploration Vehicle Propulsion Estimation

A. Ames Trajectory Browser

Analyses of deep space transits were performed in this paper with the Ames Trajectory Browser (ATB) software tool maintained by NASA Ames. [3] This trajectory browser is a publicly available tool that compiles previously calculated, first order trajectory estimates for one-way or round-trip Earth departures to select solar system locations, including Mars.

The trajectories identified in this section are considered first order estimates, used as placeholders for rough sizing studies. Future funding/partnering is required to apply more sophisticated analysis tools necessary to further refine this vehicle design and associated mission plans.

The tool identifies possible transit dates and durations for missions. Note that the ATB computes round trips on the assumption that the spacecraft will perform a direct entry to Earth at the end of the mission and provides a reentry speed. All of the round-trip trajectories in this paper instead return to LEO, with a 400 km circular orbit assumed as a default. Consequently, Δv assessments in this paper are based on the total Δv provided by the ATB, plus the reentry speed, minus an orbital velocity of 7.8232 km/s (17,500 mph). This will estimate a propulsive capture into LEO as the DSEV does not contain the heat shielding necessary for aerobraking or aerocapture.

A key limitation of the ATB software tool is that it currently cannot estimate round trip Mars trajectories departing Earth in years later than 2037. The 2037 limitation impacted this analysis by limiting this study to dates within the tool's capability. As part of the sizing of the DSEV, its ability to support human missions to Mars within a ten-year mission cadence was assessed and is shown in Table 1. The 2037 limitation consequently constrained that analysis to Earth departures in the time period 2028-2037. This date range is NOT a program recommendation and there is no recommendation implied for DSEV missions within this timeframe. Further, there is no intention in this paper to recommend any actual dates whatsoever.

A goal was to maximize the number of Mars missions during this ten-year time period. To accomplish this, two DSEVs are used. This allows one expedition to depart for Mars while the preceding one is still in transit returning to Earth. Long transfers that might place two crews on Mars simultaneously were avoided when selecting trajectories using the ATB. Also avoided were long transfers that would have required a third DSEV (due to one expedition needing to depart Earth while neither of the two preceding expeditions have returned) It is worth noting that a continuous human presence on the Mars surface is possible but achieving such would require at least one more DSEV. (In order to establish a transportation architecture that places crew on Mars without interruption, a minimum of three DSEVs are required. Otherwise, gaps in human presence would occur where gaps emerge because two would still be in transit or at Mars at the time a third would need to depart Earth.) It would also either require a second base camp to account for substantial periods of overlap where DSEV transit times lead to two crew on the surface for extended periods of time, or a significant Mars orbital mission (such as a Phobos or Deimos excursion) for when two expeditions are in the Mars system.

Table 1. Common Habitat Architecture Mars Mission Opportunities

Mission	Spacecraft	Earth Departure	Mars Arrival	Mars Departure	Earth Arrival	Stay Time (days)	Round Trip Time (days)	Time Base Camp Uncrewed after Crew Departure (days)
Mars Human Landing 1	DSEV 1	23-Feb-31	19-Sep-31	27-Jan-33	23-Aug-33	496	912	272
Mars Human Landing 2	DSEV 2	17-Apr-33	26-Oct-33	9-May-35	17-Nov-35	560	944	256
Mars Human Landing 3	DSEV 1	26-Jun-35	20-Jan-36	17-Jul-37	25-Jan-38	544	944	272
Mars Human Landing 4	DSEV 2	3-Sep-37	15-Apr-38	30-Dec-39	31-Jul-42	624	1792	

B. LEO Propellant Depots

This architecture assumes the use of orbital depots to stockpile the propellant needed for DSEV missions. The use of a depot allows refueling flights to be launched ahead of any given expedition, prior to crew launch, thereby reducing mission risk from delays in refueling flights. Sizing estimates are based on the use of Starship variants as both orbiting depots and as tankers due to the large cargo lift and propellant stowage capacities of Starship. It is further assumed that 90 tons of Starship's predicted 100-ton payload [4] capacity is transferrable propellant and that the Starship main propellant tanks can be used for propellant stowage. Three depot Starships are used in this architecture – one xenon depot and two LOX/CH4 depots. The LOX/CH4 depots each carry a Propellant Depot System payload that provides power, high-capacity pumps, and cryocooling to maintain LOX and LCH4 for long durations in their propellant tanks. These depots are each Earth ascent-entry Starships that can return to Earth for maintenance and upgrades as needed. The xenon depot Starship is similar, except that it repurposes its LOX and CH4 tanks to store xenon once in orbit and has heaters in place of cryocoolers. This does eliminate its ability to return to Earth on demand. Each tanker is launched to its target depot, docks, transfers propellant, undocks, and returns to Earth for reuse. Twelve Xenon tanker flights and twenty-seven LOX/CH4 tanker are needed to fully fuel the DSEV for Mars expeditions. The depot Starships will dock to the DSEV propulsion elements to transfer propellant.

C. Trajectory Analyses for Other Destinations

Mars is not the only destination that can be visited by the DSEV. (For purposes of this discussion, Phobos and Deimos missions are considered a subset of Mars missions.) Even within a campaign of human Mars missions there are options between Mars expeditions to conduct flights to other locations. Using the Ames ATB, mission opportunities are identified for non-Mars missions, primarily those that can utilize the DSEV in-between human Mars missions.

The DSEV does not have the performance to conduct an orbital mission to Mercury, but it could complete a Mercury fly-by mission. A mission opportunity departs Earth on January 1, 2035, passes Mercury on November 17, 2035, and arrives at Earth on January 6, 2037. This 736-day mission is well within the DSEV's nominal mission envelope. Based on the current architecture, DSEV 2 is available at the time of this opportunity.

There are both long and short-stay opportunities for human missions to Venus as shown in Table 2. The two short-stay opportunities allow for 30 and 65 days in orbit. Both short-stay opportunities tie very well with the HAVOC concept [5] developed at the Langley Research Center, with the DSEV serving as the in-space transit vehicle. The 464-day long-stay opportunity would either require a long duration Venus skyship or would require an orbital mission architecture for the time not spent in the Venus atmosphere. DSEV 2 is available for all three opportunities.

Table 2. Venus Mission Opportunities Within Common Habitat Architecture

Earth Departure	Venus Arrival	Venus Departure	Earth Arrival	Venus Stay Time (days)
2-Jun-31	5-Oct-31	9-Dec-31	18-Nov-32	65
23-Dec-35	5-Jul-36	4-Aug-36	21-May-37	30
20-Jan-36	30-Jul-36	6-Nov-37	10-Feb-38	464

Near-Earth Asteroid (NEA) Itokawa is also accessible to the DSEV. A mission opportunity with a 112-day stay time at the asteroid departs Earth on June 28, 2030. It reaches Itokawa on September 19, 2031 and departs on January 9, 2032. It arrives back in LEO on April 1, 2033. DSEV 2 is available for this opportunity.

Another NEA, Bennu, is accessible to the DSEV. Earth departure is March 17, 2036. Arrival at the asteroid is November 17, 2036 and it departs the asteroid on December 7, 2036 after a 20-day stay time. The DSEV arrives back at Earth on March 17, 2037. DSEV 2 is available for this mission.

NEA 2008 EV5 can be reached with an Earth departure of June 28, 2038, asteroid arrival of April 6, 2039, departure on May 6, 2039, and Earth return on December 22, 2039. DSEV 1 is available for this mission.

A DSEV mission to NEA 2009 BD can leave Earth orbit on December 8, 2033, arrive at the asteroid on June 16, 2034, depart after 30 days on July 16, 2034, and arrive at Earth on May 22, 2035. DSEV 1 is available for this mission.

The NEA 2011 MD is accessible via the DSEV with an Earth departure of June 20, 2036, asteroid arrival of April 1, 2037, departure 30 days later on May 1, 2037, and Earth arrival on December 17, 2037. DSEV 2 is available for this mission.

No orbital rendezvous missions to main belt asteroids closed within the Ames ATB. (This is not to say that such missions are not achievable, only that the limited set of trajectories in the ATB did not include a suitable trajectory. More extensive analysis is not available within the limitations of this study.) However, a fly-by mission to main belt asteroid Vesta, the second-largest asteroid and the brightest one visible from Earth, did close. An opportunity for a Vesta fly-by departs Earth on August 2, 2031, passes the asteroid on January 1, 2035, and arrives back at Earth on August 15, 2036. At 1840 days (5.04 years), this does exceed the 1200-day design parameter of the Common Habitat, though it is not clear if longer missions might be acceptable from a habitability perspective. Neither DSEV is available for this opportunity and a third DSEV equipped with four Logistics Modules would be required to conduct this mission.

Surprisingly, an orbital Jupiter mission appears to be at the upper limit of the DSEV's capability. The lowest delta-v mission opportunity identified by the ATB (12.0868 km/s) departs Earth on August 23, 2033, arrives at Jupiter on October 21, 2037, departs Jupiter after a 112-day stay on February 10, 2038, and arrives back at Earth on July 9, 2040. As with Vesta, neither DSEV is available for this opportunity and a third DSEV would be required to conduct this mission. Of course, it is obvious that all of the problems with long duration missions – radiation exposure, food and medicine shelf life, microgravity deconditioning, etc. – are orders of magnitude worse for a Jupiter mission. Further, at 2512 days (6.88 years) this is far beyond the durations considered during the Common Habitat's development and would require six Logistics Modules. It is unlikely that a DSEV could overcome these problems sufficiently to seriously consider a Jupiter voyage. However, this analysis does serve as a starting point to begin to consider what it might mean for humanity to venture beyond the inner solar system.

V. Deep Space Exploration Vehicle Major Elements

A. Pressurized Elements

The DSEV utilizes many of the components of the surface base camp Habitation Zone and Power Zone, with some changes in configuration. The pressurized elements in particular include the Common Habitat, Two-Chamber Airlock Node (TCAN) [6], Pressurized Rovers for In-Space Missions (PRISM), and one or more Logistics Modules (LMs). [7] The Common Habitat is connected to attached elements via appropriately sized multi-gravity active-active mating adapters (MGAAMAs). [2] The Common Habitat was already shown in Figure 1 – Figure 4 and the remaining individual elements are illustrated in Fig. 5 – Fig. 8.

Fig. 5 Two-Chamber Airlock Node (TCAN)

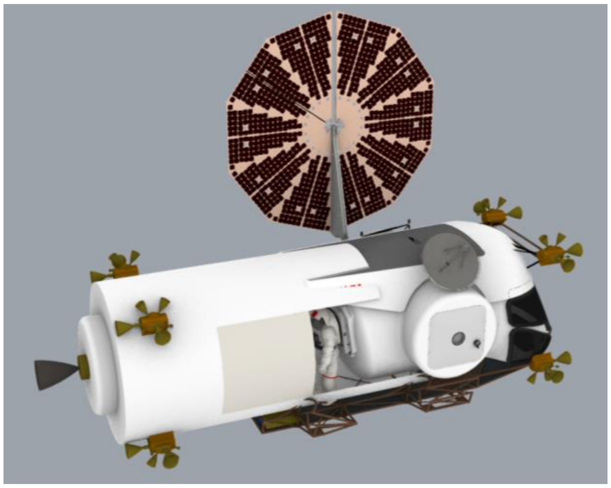

Fig. 6 Pressurized Rover for In-Space Missions (PRISM)

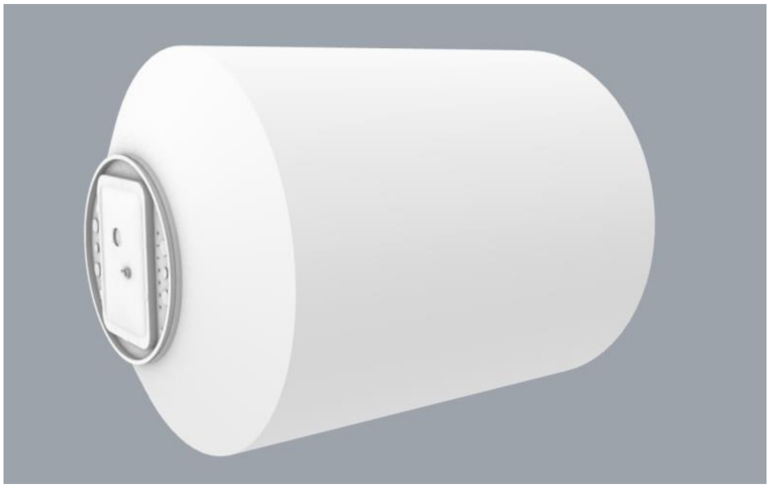

Fig. 7 Logistics Module (LM)

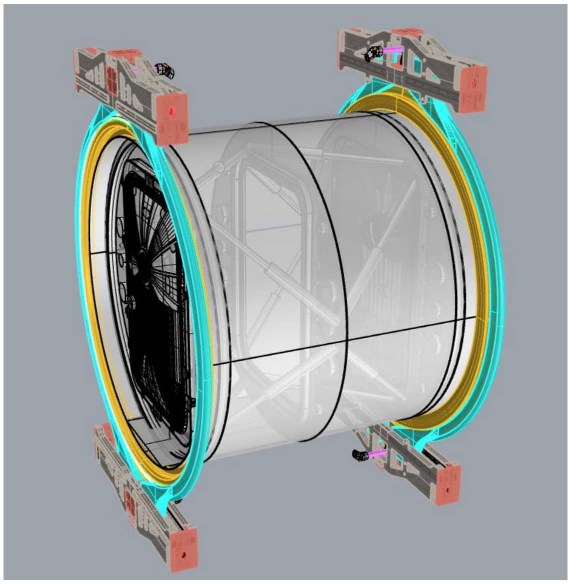

Fig. 8 40-inch x 60-inch to 40-inch x 60-inch Multi-Gravity Active-Active Mating Adapter (6x6 MGAAMA)

NASA previously considered in-space variants of the PRs immediately after the cancellation of the Constellation program. NASA had been directed at the time to explore a deep space mission to a Near-Earth Asteroid. As part of that effort, a Deep Space Habitat was designed to provide habitation during the round trip transit, [8] but a Lunar Electric Rover was adapted by replacing the chassis with a propulsion module to serve as the local exploration vehicle that would detach from the DSH to conduct the actual exploration, with the resulting spacecraft named the Multi-Mission Space Exploration Vehicle (MMSEV). The thinking at the time was that the MMSEV would separate from the DSH to perform close exploration of the asteroid body. [9] A significant amount of design, simulation, and even human-in-the-loop testing was performed on the MMSEV before the deep space asteroid mission was cancelled. A variation on the MMSEV is considered for the PRISM. The wheeled chassis is removed, a propulsion service module is added behind he suitports, and RCS thrusters are placed around the vehicle.

The number of logistics modules present is determined by mission duration. Common Habitat Docking port assignments are driven by the goal to reduce loads on the MGAAMA, placing the heaviest elements (Logistics Modules) in-line with the thrust axis, thereby restricting them to the forward and aft docking ports.

For missions where only a single logistics module is required, it is docked to the Common Habitat aft docking port, the TCAN to the forward port, and one PRISM each to the port and starboard docking ports. In this case one of the three 6x6 MGAAMAs is left behind and an additional 4x6 MGAAMA is carried in its place. (MGAMMAs not used on a particular DSEV mission can be left behind in LEO in the cargo bay of the Xenon Depot Starship.) Some Venus orbital missions, and some Near-Earth Asteroid missions fall in this category, including some trajectories to reach the asteroid Itokawa.

For missions where two logistics modules are required, one is docked to the Common Habitat aft docking port and the other to the forward port. The TCAN is docked to the starboard port and the two PRISM are docked to each other, with one also docked to the Common Habitat port docking port. All Mars missions fall within this category, as does a Mercury flyby, some asteroid missions (including some Itokawa trajectories), and some Venus orbital missions. The baseline configuration of pressurized elements is shown in Fig. 9.

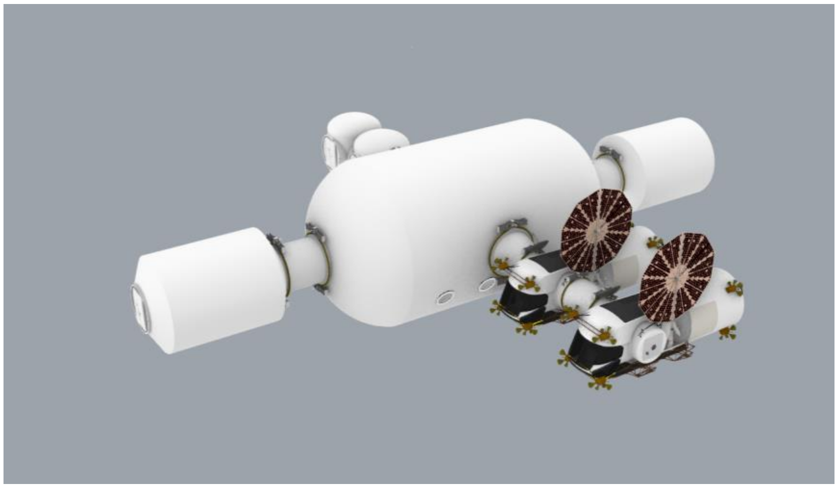

Fig. 9 DSEV Pressurized Elements

B. Unpressurized Elements

The core of the unpressurized segment of the DSEV is a trio of modified Starships that serve as the main propulsion system of the DSEV. Two are LOX/CH4 chemical propulsion Starships that operate in a manner similar to a traditional Starship, except that they are part of a larger spacecraft stack.

The third is a nuclear electric propulsion Starship. Its propellant tanks are filled with Xenon instead of oxygen and methane. It extends a tower with a roughly 2-megawatt nuclear power element (from the surface Power Zone) and twin booms, each terminating in electric propulsion thrusters. It deploys an approximately 3000 m^2 radiator. It contains a large remote manipulator system (RMS) that it uses to deploy an interstage segment. The three Starships use a mechanism analogous to the Joinable Undercarriage to Maximize Payload (JUMP) Mating Mechanism [10] to structurally mate to each other.

The DSEV propulsion system is sized to be capable of a total mission Δv of at least 12 km/s. This is a rough estimate calculated using a hybrid propulsion architecture consisting of LOX/CH4 chemical propulsion with a 361 second Isp and Xenon nuclear electric propulsion with an intentionally very conservative 1200 second Isp. By comparison, the Gateway Power and Propulsion Element has an Isp of 2400 seconds. [11] The chemical Isp is tied to known engine performance and the 1200 second Isp is intentionally very conservative as the electric thrusters have not been identified. Any actual thruster is likely to have a significantly greater specific impulse, leading to an increased Δv. The mission Δv is estimated using the rocket equation, $\Delta v = g_o \, Isp \ln(\frac{m_1}{m_2})$.

The interstage is the structural member connecting the nuclear electric propulsion Starship to the Common Habitat's aft ring frame. It encircles the aft Logistics Module like an unpressurized garage and has sufficient open space that the RMS can be used to dock/undock the Logistics Module. The interstage also contains the DSEV communications transmitters and receivers. Fig. 10 shows a Logistics Module docked to the Common Habitat and contained within the interstage.

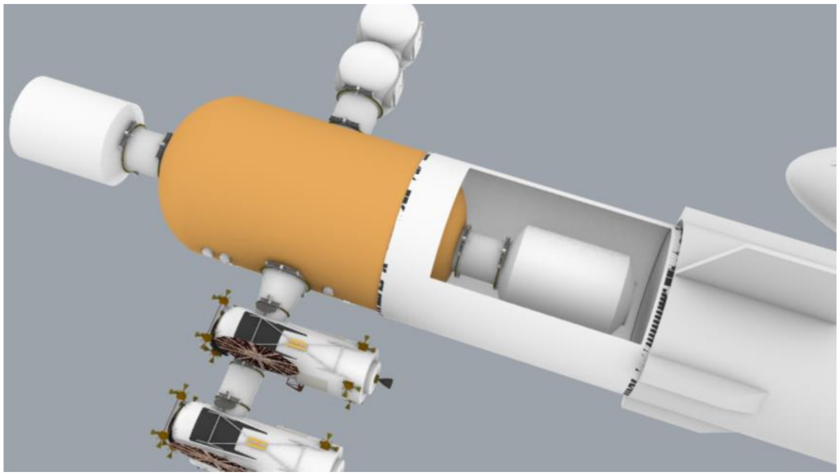

Fig. 10 Logistics Module within the Interstage Docked to the Common Habitat

The interstage also has mounting locations where additional Logistics Modules can be berthed. The interstage is equipped with six passive flanges compatible with the MGAAMA, each of which constitutes a berthing port. Up to six Logistics Modules or a combination of Logistics Modules and other elements can be berthed to the interstage. These ports do not provide for any form of pressurized connection, water, or gas exchange with the Common Habitat, but do permit power, data, and thermal fluid connectivity. If any additional logistics modules are required beyond the two docked to the Common Habitat, the others are not docked to the Common Habitat, but are instead berthed to one of these ports. They will not be docked to the Common Habitat until one of the docked logistics modules is depleted, at such time the depleted module is replaced with a fresh one.

For missions of 108 days or less, no logistics modules are required but may still be used to assist with safe haven or trash management methodologies. For missions from 109-641 days in duration, a single logistics module is required. The DSEV has thus far only been assessed for missions up to 1200 days, for which two logistics modules are required. Should longer missions be considered at some point, a third logistics module would need to be carried on the stack for missions up to 1706 days or a fourth for missions up to 2239 days. These longer durations are unlikely unless the DSEV were used to a distant destination such as Jupiter, which requires six Logistics Modules.

Fig. 11 shows the DSEV with all six berthing ports on the interstage berthed to Logistics Modules. This configuration represents the theoretically longest mission the DSEV can support, though it is unreasonable to assume a mission that would require the 4377 days (11.99 years) of consumables that could be contained in eight Logistics Modules – two docked to the Common Habitat and eight berthed to the interstage. (Nor would the shelf lives of consumables permit a mission of such duration.) It is far more likely that these berthing ports would instead be used for additional MGAAMAs to support visiting vehicles or mission-specific science platforms.

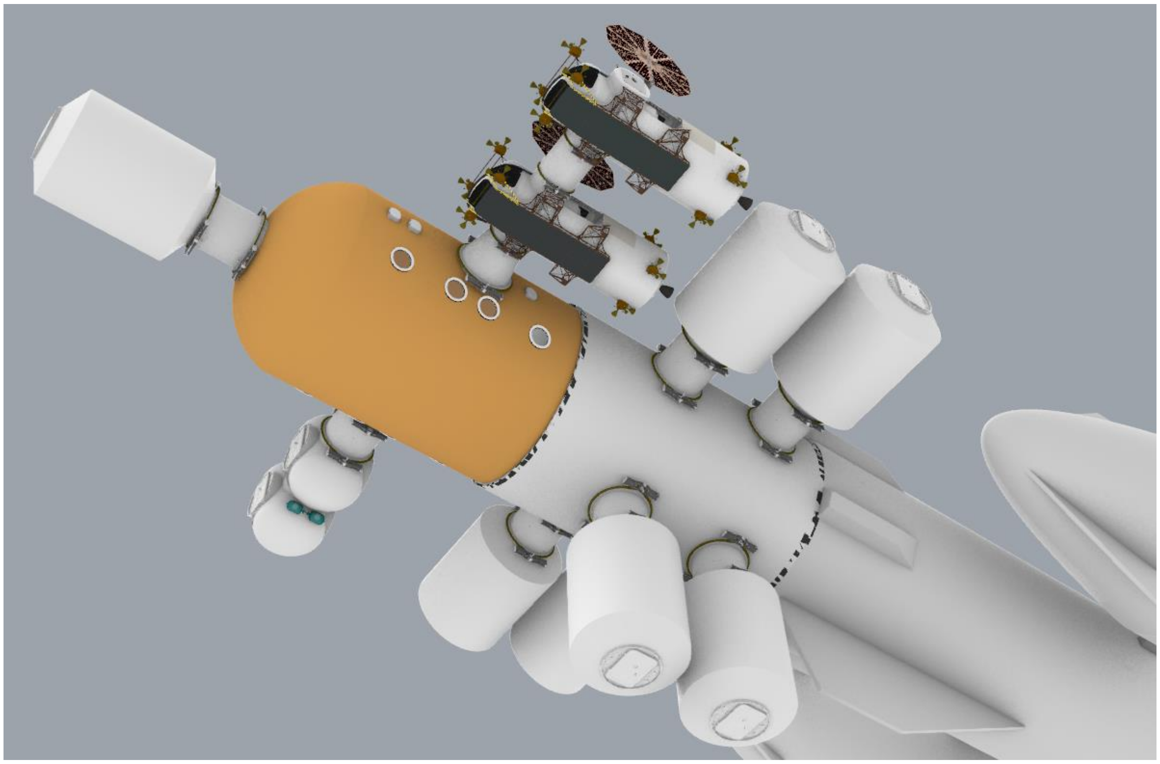

Fig. 11 Deep Space Exploration Vehicle with Logistics Modules on all Berthing Ports

A dozen external, telemetered science instruments are located on the exterior of the DSEV, some on the Common Habitat and others on the interstage. These include interferometric telescopes, dust sensors, particle analyzers, and field detectors. Figure 12 shows the entire DSEV spacecraft stack, from the Logistics Module docked to the forward end of the Common Habitat, all the way to the fission reactor and radiation shield extending from the nuclear electric propulsion Starship at the far aft of the vehicle.

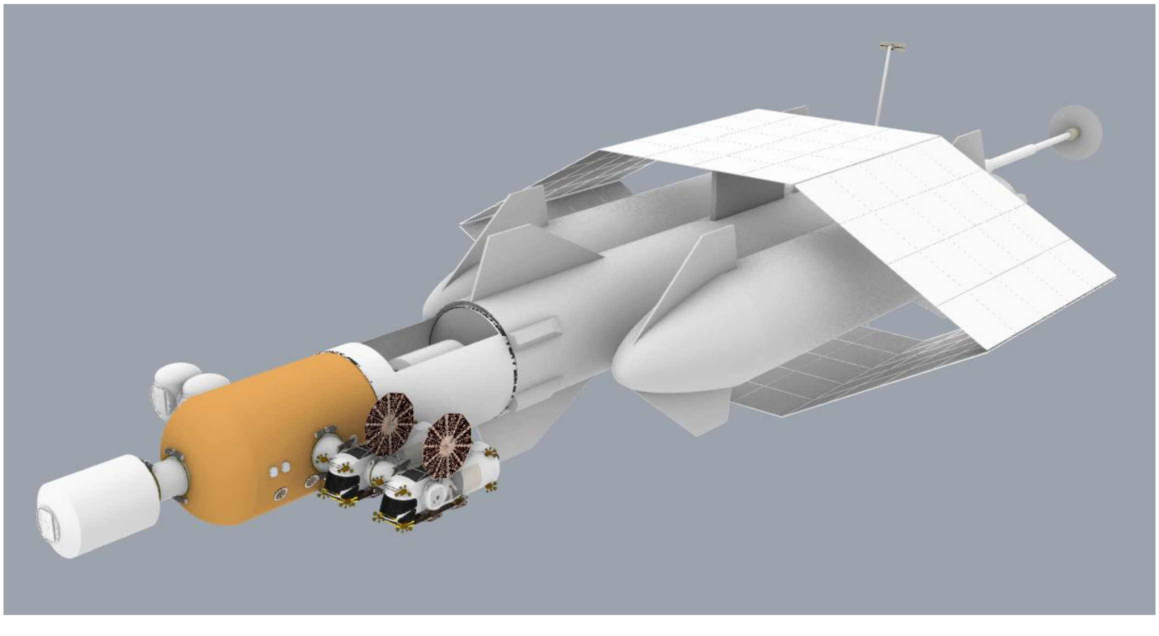

Fig. 12 Deep Space Exploration Vehicle

VI. Deep Space Exploration Science

While there is no limit to the depth of scientific investigation in any domain, the specific capabilities of the DSEV do lend itself to specific modes of scientific research. The DSEV Common Habitat carries an identical science outfitting to the base camp, including space biology, human research, physics, remote sensing, and geology laboratories. [12]

The Geology Laboratory is worthy of special discussion because it has often been especially overlooked in Mars Transit Vehicle concepts. However, for both Mars and other destinations, there is value in performing in situ geology science (e.g. with samples that exceed the architecture's capacity to return to Earth, samples that help select other samples for Earth return, etc.). These cases provide rationale for the Common Habitat to include a geology laboratory, to perform science on those samples that are not intended for return to Earth and are instead identified for in situ analysis.

The DSEV has an additional geologic potential that may involve mission-specific payloads. For low gravity destinations in particular (e.g. Phobos, Deimos, and NEAs) it is possible to recover literally tons of native material. As an example, the DSEV could be tasked to conduct an expedition to recover the roughly 6-meter diameter asteroid 2014 WX 202. [13] The Ames ATB indicates a ~490-day mission opportunity for such a mission that could conceivably be performed by DSEV 1. Departing Earth on October 24, 2033 and returning on February 26, 2035, the mission would include a 30-day stay time. Because this mission duration requires only one LM, the second LM could be replaced by an asteroid capture system that would encapsulate the entire asteroid in a module that could be delivered to an entry spacecraft in LEO for Earth landing. (This of course assumes that the DSEV can still achieve the Earth return Δv with the additional mass of the asteroid.)

The DSEV carries an inherent ability to advance artificial gravity research. (While the Human Research Lab includes two small centrifuges, they largely are not part of the artificial gravity focus.) A large centrifuge occupies a significant amount of floor space in the life sciences section of the deck This centrifuge is large enough to house chambers for small animal enclosures (small rodents, birds, fish, etc.) However, the most extensive artificial gravity research capability is enabled by the two PRISM spacecraft. The rovers can be used to validate control of artificial gravity spacecraft and measure human performance impacts of artificial gravity under varying lengths of exposure and at different gravitational levels.

The PRISM can separate from the DSEV during non-accelerating periods with a tether deployment system connecting their zenith surfaces. (The pressurized rover cabins are designed for multiple gravity environments just like the Common Habitat.) After moving away from DSEV, the PRISM can fire attitude control thrusters to spin up and deploy the tether. They can achieve different gravity test points by controlling thruster Δv and tether length. The tether can be deployed to progressively increasing lengths up to 500 meters and can accelerate their rotational velocity to achieve different gravity levels (e.g. 1/6g, 3/8g, 1g, etc.) Fig. 13 shows two PRISM at a 40-meter separation and Fig. 14 shows two PRISM at a 200-meter separation. Four crew can live onboard the two PRISM for increasing periods of artificial gravity, perhaps starting with periods of only a few hours, but extending to up multiple days. (1 day, 3 days, 7 days, 14 days, up to 30 days) Human performance measurements can be conducted inside the PRISM during artificial gravity exposure with the limited instrumentation that can be brought aboard a PRISM cabin, including remote monitoring by the crew remaining onboard the Common Habitat. Following each test series, the PRISM can spin down, retract the tether, and return to Common Habitat, where more extensive physical examinations can be conducted.

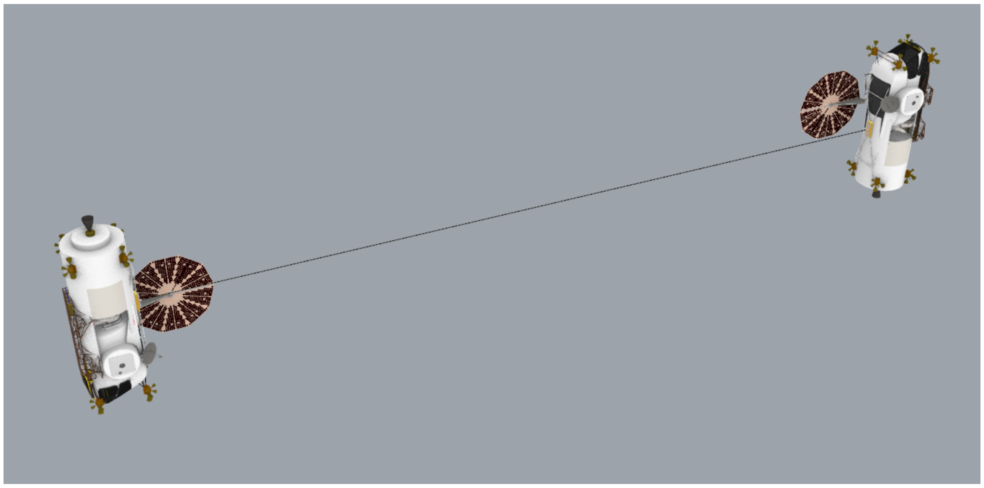

Fig. 13 Artificial Gravity Test with PRISM at 40-meter Separation

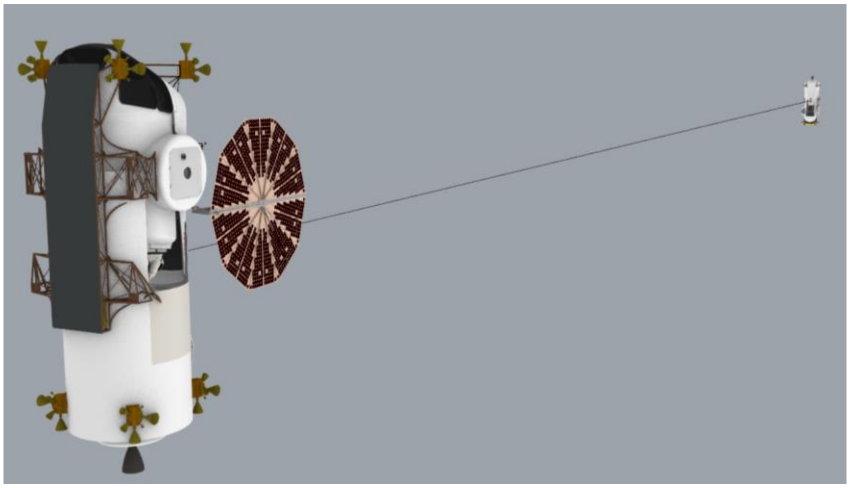

Fig. 14 Artificial Gravity Test with PRISM at 200-meter Separation

VII. Deep Space Exploration Vehicle Launch and Assembly

The DSEV is assembled in LEO, leveraging experience gained with assembly of the International Space Station and taking advantage of real-time communications. A LEO assembly also maximizes the number of elements (total mass) that can be delivered in a single launch   From a physics and budgetary perspective, a launch vehicle capable of delivering 100 tons or greater to LEO at a launch cost roughly less than or equal to the $62M advertised costs for the Falcon 9 is required to support this architecture. [14] It is presumed in this analysis that such a vehicle would be available. For purposes of this paper, the SpaceX Starship is used as an example of this capability

The required capability must also contain sufficient volume to accommodate each manifest and to derive a packaging and deployment scheme. Notional manifests have been established to deploy and assemble the DSEV in three cargo launches.

Assuming these capabilities:

- Cargo Launch 1 contains most of the unpressurized elements of the DSEV and establishes its propulsion, power, thermal, and communications capability. The cargo includes twelve electric propulsion thrusters, radiator assembly, ~2 MW fission nuclear reactor, communications array, RMS, interstage, and approximately 25 tons of propellant.
- Cargo Launch 2 is dedicated exclusively to the Common Habitat as the only payload.
- Cargo Launch 3 completes the DSEV. Its cargo includes two PRISM, one IDSSx4 MGAAMA, one 4x4 MGAAMA, three 6x6 MGAAMA, one 4x6 MGAAMA, the TCAN, twelve external telemetered science instruments, and two logistics modules.

There are at least two options for the disposition of the three Starships used to launch the DSEV components. Ideally, the three launch vehicles are the DSEV propulsion modules. Should this not prove feasible, the next best approach is for the three launch vehicles to be reusable cargo Starships that can launch the components of the second DSEV and continue to be used for other unrelated missions. It remains as forward work to verify that the Starship shroud can be lengthened as needed to perform DSEV element launch. The 15-meter long Common Habitat is too long for the baseline Starship shroud [4] and a 7.68-meter increase in barrel length is needed to accommodate the habitat. This stretched shroud is assumed for all missions with Common Habitat payloads and as forward work may be used for other missions in this architecture as well.

VIII. Mars Crewed Mission Example

A. DSEV Fueling

Prior to crew mission Earth departure, the LEO Depot is fueled with propellant. A total of 27 LOX/CH4 tanker Starship flights and 12 Xenon tanker Starship flights are launched to fill the three Depot Starships for a Mars mission. The Depot starships will individually dock to the DSEV and fuel their counterpart DESV Starships. Once DSEV fueling is complete, logistics and crew launches can occur.

B. Logistics Launch

Each LM is estimated to mass 30 tons. Because the DSEV stages in LEO, the LM mass is well within the performance envelope of most of the world's heavy commercial launch vehicles. Therefore, many options exist to deliver LMs to the DSEV either as dedicated logistics launches or potentially even co-manifested with other launch missions. In the case of super-heavy commercial launch vehicles, it is even possible for a LM to fly as a secondary payload or to launch more than one in a single flight.

C. Crew Launch

Given the current and projected global launch capability, there is more than one way to deliver eight crew to the DSEV in LEO. The baseline is to launch all crew on SLS/Orion, but a nominal SLS/Orion launch only accounts for four crew. At least five options exist to deliver eight crew to the DSEV:

(1) Four crew launch on SLS/Orion to LEO and utilize a commercial crew opportunity to launch the remaining four crew on a commercial vehicle. Because this would result in different arrival times it is possible that the four crew who arrive first might have a secondary mission, possibly some form of pre-mission vehicle configuration. If some of the crew are launched on a Starship, it could be possible to co-manifest both crew and logistics on a single launch.

(2) Four crew launch on SLS/Orion and utilize an international opportunity to launch the remaining four crew on one or more international vehicles. This has the advantage of moving the launch of the non-Orion crew entirely away from the NASA budget, assuming the cost of this launch is borne by the international provider.

(3) Launch two four-crewed Orion spacecraft on one SLS. Given that the destination is LEO, two Orion spacecraft would fit within the mass performance envelope of a single SLS. However, it is likely that the second Orion could not have a Launch Abort System attached. This might be a nonstarter depending on SLS reliability at the time such a decision would need to be made.

(4) Use two SLS launches to conduct two four-crewed nominal SLS/Orion flights to LEO.

(5) Use commercial crew launches exclusively to deliver all eight crew to the DSEV. One example would use a crew/cargo orbital Starship to deliver all eight crew and two LMs in a single flight. This option might be used in the event of a fully commercial DSEV mission, such as a NEA commercial mining expedition. (It is possible that different DSEV expeditions may be conducted for different entities, much like the Department of Defense conducted several space shuttle missions.)

These options are not mutually exclusive. Some expeditions could be conducted under one option while others are conducted under another.

D. Outbound Cruise

The outbound transit is a deep space microgravity science mission in and of itself. The deep space environment is a higher radiation environment than that experienced in LEO and the centrifuges and artificial gravity experiments create different conditions than those experienced on the International Space Station. Space biology science is inclusive of plant, animal, insect, cellular, and molecular investigations. The human research focus is similar but is focused on protecting astronauts from the five key hazards of spaceflight: radiation, isolation and confinement, distance from Earth, gravity, and hostile/closed environments. [15] Physics encompasses biophysics, combustion science, complex fluids, fluid physics, fundamental physics, and materials science research. Remote sensing includes control of the external science payloads, including various telescopes and detectors. While the telescopes and detectors can be operated by Mission Control, due to the time delay the crew is able to take independent actions in the conduct of remote sensing research.

E. Mars Orbit

A typical Mars mission will see all eight crew depart the DSEV for the Martian surface. Once in Mars orbit, the crew will prepare to depart the DSEV for the surface. Generally, the DSEV will not dock with the Mars lander vehicle. Instead, the lander will rendezvous, and hold position several kilometers away. The crew will use the PRISM to fly the short distance to the lander. Once the crew have transferred over to the lander the PRISM will return to dock with the Common Habitat.

During the surface mission, the DSEV will operate as an uncrewed science platform. The crew will be able to access its subsystems and command it remotely from the Mars base camp. While the DSEV can serve as a contingency communications relay for the base camp, the primary communications architecture is a Lagrange-based network [16] that will be described in greater detail in a future paper.

At the end of the surface mission, the lander or ascent spacecraft will lift off, delivering the crew and surface samples cargo to orbit where the PRISM will dock to recover the crew and transport them the remainder of the distance to the DSEV.

F. Inbound Cruise

The inbound cruise is a similar science mission to the outbound cruise with one key exception. The DSEV is now carrying samples collected during the surface mission, outbound cruise, and inbound cruise. Those intended for transport to Earth are cached in either conditioned or unconditioned stowage and will not be disturbed by the crew. However, some samples will be designated for in-space analysis, involving a mixture of biology, physics, and geology investigations. The samples in question may include solids, fluids and gases fabricated on Mars, collected geology and atmospheric samples, engineering samples from the DSEV or surface elements, human research and space biology samples, and interplanetary samples.

G. Earth Arrival

As the DSEV approaches Earth and ultimately reaches orbit, crew activity will shift to begin winding down crew-operated science investigations. Vehicle inspections will be conducted to determine any needed repairs or replacements. The crew will depart the DSEV with all Earth return samples. This may include both the samples designated for in-space analysis and those that were cached for return to Earth with no crew contact. Just as with crew launch, options for return to Earth include Orion, commercial spacecraft, and international spacecraft. Once the crew has departed, the DSEV is available for roughly 600-700 days until the next Mars mission. While the DSEV can operate as an uncrewed science platform during this time it is more likely that it will be crewed and used for one or more of the other crew missions previously discussed (e.g. Mercury fly-by, Venus, Itokawa, 2008 EV5, 2009 BD, 2011 MD, etc.) or even as a temporary LEO space station.

IX. Conclusion

The DSEV is a highly capable, multi-mission, multi-destination science exploration spacecraft that enables unprecedented objectives in human spaceflight throughout the inner solar system. It can reach destinations of interest such as Venus and Near-Earth Asteroids without the need of a separate development effort. It can conduct flyby missions to bodies that have previously been considered beyond human reach, such as Mercury and Vesta. Specific to Mars, it provides substantially greater IVA science capability than predecessor DST and DSH concepts. It also includes emergency facilities intended to save crew lives that might otherwise be lost under certain vehicle contingencies – namely the Common Habitat's maintenance facilities and the DSEV Safe Haven mode. [17] It can be developed with many of the same technologies needed to develop long-duration outposts on the Moon and Mars. While this initial work establishes the concept and feasibility of the DSEV, significant forward work remains that can be pursued as funding and partnerships permit.

Forward work includes PRISM Service Module sizing and outfitting. The PRISM functionality may include orbital transfers in both the Earth-Moon system and the Mars system. Further study is needed to determine what range of transfers should be allocated to the PRISM and whether it can refuel from the Starship chemical propulsion modules.

Work is also needed to determine whether the PRISM can land on NEAs, Phobos, or Deimos. The landing configuration will also impact solar array and radiator configurations. A power trade may also be relevant to consider options among solar arrays, fuel cells, and batteries. In the area of contingencies, it will be important to identify escape and rescue options from a disabled PRISM and any needed changes to the DSEV to improve survivability options. Possible options include the use of derivatives of the Manned Maneuvering Unit (MMU) or Simplified Aid for EVA Rescue (SAFER) [18] or other free-flying systems.

In the area of EVA systems, Single-Person Spacecraft (SPS) EVA options should be assessed, including a suit port compatible SPS. [19]

The DSEV interstage is presently notional. Structural design input is needed to properly size the interstage and generate accurate mass estimates.

The DSEV includes a remote manipulator system. Forward work is to establish a baseline RMS design, including either a rail system to enable the arm to translate across different elements of the DSEV or an ability for the arm to walk itself across the spacecraft stack. Work is also needed in the area of end effector design.

Additional refinement is needed for all of the CAD models of the DSEV and its constituent elements.

The Δv to return to LEO from a deep space mission is significant and perhaps worthy of assessment in trade studies. If the DSEV were returned to a higher orbit than LEO, the amount of propellant it would need to carry would be significantly reduced. However, the number of Starship launches to refuel the DSEV would greatly increase. Similarly, alternate orbits at destinations and interplanetary trajectory refinements may identify additional propellant savings but should be balanced against potential burdens placed on landers and ascent spacecraft.

Acknowledgments

The author offers thanks to the many Agency volunteers and university students who have supported Common Habitat design and evaluation activities over the years. Thanks are also offered to the Johnson Space Center EMERGE Employee Resource Group, Center for Design and Space Architecture, and the NASA Center of Excellence for Collaborative Innovation. Finally, thanks are offered to all team members of current and prior NASA lunar, Mars, and deep space architecture studies.

References

[1] Howard, R., "Opportunities and Challenges of a Common Habitat for Transit and Surface Operations," *IEEE Aerospace 2019*, IEEE, Big Sky, MT, 2019.

[2] Howard, R, "A Multi-Functional Two Chamber Airlock Node for a Common Habitat Architecture," *AIAA ASCEND 2021*, AIAA, Virtual Conference, 2021.

[3] Foster, C., "NASA Ames Research Center Trajectory Browser," *NASA Ames Web-based Trajectory Generation Tool* [online database], URL: https://trajbrowser.arc.nasa.gov/ [retrieved 18 June 2021].

[4] SpaceX, "Starship User's Guide Revision 1.0 March 2020," URL: https://www.spacex.com/media/starship_users_guide_v1.pdf [retrieved 4 July, 2021].

[5] Arney, D., Jones, C., "HAVOC: High Altitude Venus Operational Concept," *AIAA Space 2015*, AIAA, Pasadena, CA, 2015, URL: https://arc.aiaa.org/doi/abs/10.2514/6.2015-4612 [retrieved: 10 June 2021].

[6] Howard, R. "A Multi-Gravity Docking and Utilities Transfer System for a Common Habitat Architecture, *AIAA ASCEND 2021*, AIAA, Virtual Conference, 2021.

[7] Howard, R. Stowage Assessment of the Common Habitat Baseline Variants. AIAA ASCEND 2020, Virtual Conference, 2020.

[8] Rucker, M., Anderson, M., "Issues and Design Drivers for Deep Space Habitats," *Global Space Exploration Conference*, International Astronautical Federation, Washington, DC, 2012, URL: https://ntrs.nasa.gov/citations/20120008543 [retrieved 25 June 2021].

[9] Kennedy, K, "HDU Deep Space Habitat (DSH) Overview," *41st International Conference on Environmental Systems*, ICES Organizing Committee, Portland, OR, 2011, URL: https://ntrs.nasa.gov/citations/20110008769 [retrieved 25 June 2021].

[10] Howard, R., "An Initial Concept for a JUMP Mating Mechanism," *AIAA ASCEND 2020*, AIAA, Virtual Conference, 2020.

[11] Herman, D., Gray, T., Johnson, I., Kerl, T., Lee, T., Silva, T, "The Application of Advanced Electric Propulsion on the NASA Power and Propulsion Element (PPE)," *36th International Electric Propulsion Conference*, Electric Rocket Propulsion Society, Vienna, Austria, 2019, URL: http://electricrocket.org/2019/651.pdf [retrieved June 26, 2021]

[12] Howard, R., "A Common Habitat Base camp for Moon and Mars Surface Operations," *AIAA ASCEND 2021*, AIAA, Virtual Conference, 2021.

[13] Mou, J., Webster, I., "2014 WX202 - Very Small Apollo-class Asteroid," *Space Reference* [online database], URL: https://www.spacereference.org/asteroid/2014-wx202 [retrieved 26 June 2021].

[14] SpaceX, “Capabilities &Services,” [online], URL: https://www.spacex.com/media/Capabilities&Services.pdf [retrieved 4 July 2021].

[15] Robinson, J., Waid, M., Korth, D., Rucker, M., Renfrew, R., "Innovative Approaches to Using the International Space Station as a Mars Transit Analog," International Astronautical Congress, International Astronautical Federation, Washington, DC, 2019, URL: https://ntrs.nasa.gov/citations/20190032318 [retrieved 26 June 2021].

[16] Howard, R., Seibert, M., “Lagrange-Based Options for Relay Satellites to Eliminate Earth-Mars Communications Outages During Solar Superior Conjunctions,” *AIAA ASCEND 2020,* AIAA, Virtual Conference, 2020.

[17] Howard, R., “A Safe-Haven Concept for the Common Habitat in Moon Mars and Transit Environments,” *AIAA ASCEND 2021,* AIAA, Virtual Conference, 2021.

[18] Williams, T., Baughman, D., “Self-Rescue Strategies for EVA Crewmembers Equipped with the SAFER Backpack,” Flight Mechanics / Estimation Theory Symposium, NASA Goddard Space Flight Center, Greenbelt, MD, 1994, URL: https://ntrs.nasa.gov/citations/19940031126, [retrieved 10 July 2021].

[19] Griffin, B., “Benefits of a Single-Person Spacecraft for Weightless Operations,” 42nd International Conference on Environmental Systems, ICES Organizing Committee, San Diego, CA, 2012, URL: https://ntrs.nasa.gov/citations/20120013602 [retrieved 10 July 2021].