ISSUES AND DESIGN DRIVERS FOR DEEP SPACE HABITATS

Michelle A. Rucker
NASA Johnson Space Center, Houston, Texas, USA,
michelle.a.rucker@nasa.gov

Molly Anderson*

A cross-disciplinary team of scientists and engineers applied expertise gained in Lunar Lander development to the conceptual design of a long-duration, deep space habitat for Near Earth Asteroid (NEA) missions. The design reference mission involved two launches to assemble 5-modules for a 380-day round trip mission carrying 4 crew members. The conceptual design process yielded a number of interesting debates, some of which could be significant design drivers in a detailed Deep Space Habitat (DSH) design. These issues included: Design to minimize crew radiation exposure, launch loads, communications challenges, docking system and hatch commonality, pointing and visibility, consumables, and design for contingency operations.

I. BACKGROUND

I.I NEA Design Reference Mission

The design team was directed to work to National Aeronautics and Space Administration (NASA) Design Reference Mission 34B. For the purpose of this exercise, it was assumed that the mission required 157 days transit from Earth, followed by 30 days at NEA 2008EV5, and 193 day return to Earth, for a crewed mission duration total of 380 days. Several cases were considered for launch and assembly timing. The "Hybrid 2" option selected required the habitat module to be launched 825 days before the crew arrived. Both 3- and 4-crew missions were proposed, but designers assumed a 4-crew mission as the worst case in terms of sizing.

I.II Architecture Assumptions

The Deep Space Habitat (DSH) was intended to be part of an integrated vehicle, shown in Figure 1, which also includes a Solar Electric Propulsion (SEP) module; a Cryogenic Propulsion Stage (CPS); a Multi-Mission Space Exploration Vehicle (MMSEV); and a Multi Purpose Crew Vehicle (MPCV), also known as Orion. The architecture elements would be assembled in earth orbit. For this exercise, DSH was assumed to be a single, cylindrically-shaped module

The mission begins with the DSH and SEP launch, and an unmanned loiter for up to 825 days prior to the crew's arrival in Orion. The MMSEV would be launched separately and rendezvous with the DSH and SEP. The DSH would be launched into a high elliptical earth orbit (60,000 km by 400,000 km) using a kick stage. Using the SEP, the vehicle would narrow the ellipse to 407 km by 400,000 km, to rendezvous with Orion and a CPS in low earth orbit (407 km by 407 km), then beginning the trajectory to rendezvous with the asteroid 2008EV5.

This DSH was intended to provide in-space accommodations and care for the crew, serve as the primary command center for controlling the integrated stack, and provide a work platform for science mission objectives and vehicle maintenance activities from low Earth orbit to the destination and back again. After providing the Earth departure burn, CPS would be discarded. SEP would provide in-space propulsion and power between Earth orbit and the NEA. Once at the NEA, the MMSEV would provide short duration crew sorties between the DSH and the NEA, and would remain at the NEA while the remaining elements return to Earth. Upon reaching Earth orbit, the crew would discard DSH and SEP and return to the Earth's surface in Orion.

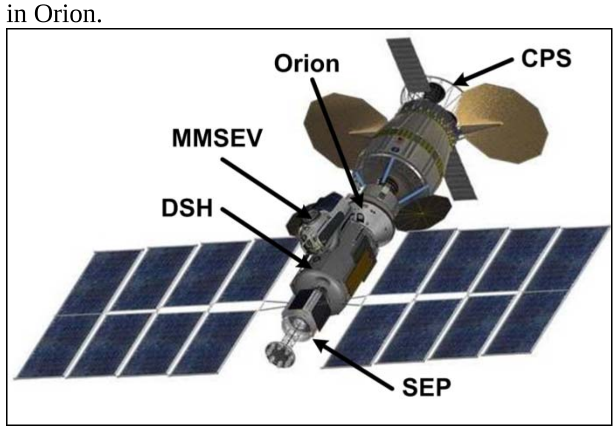

Fig. 1: Integrated Vehicle Stack

II. APPROACH

The NASA team was organized into thirteen subsystem disciplines: Command and Data Handling, Communications and Tracking, Extravehicular Activity (EVA), Flight Software, Guidance, Navigation and

* Molly Anderson, NASA Johnson Space Center, Houston, Texas, USA.

Control, Human Factors, Environmental Control and Life Support, Structures and Mechanisms, Electrical Power, Propulsion, and Thermal Control. In parallel with the individual discipline teams broadly defining each subsystem, vehicle integration specialists developed the concept of operations, decomposed the top level functional requirements, and integrated mass and equipment lists. The entire team was involved in evaluating impacts across subsystem boundaries, considering integrated vehicle performance, and settling on mutually agreeable assumptions and design decisions. Two design iterations produced a preliminary concept that was then used to support mission design trade studies, and as a parametric reference for other habitat variations.

III. GROUND RULES AND ASSUMPTIONS

Not every architecture element or module (DSH, CPS, SEP, MMSEV, Orion MPCV) has been developed to the same level of detail. Some of these elements are entirely conceptual at this point, making cross-team integration and optimization difficult. For the purpose of this exercise, certain ground rules and assumptions were established so that reasonably good choices could efficiently be made for the DSH design.

III.I MMSEV and Orion Habitation

Except for emergency safe haven use, it was assumed that the Orion and MMSEV would only be used for equipment stowage—not habitation—while the integrated vehicle was in transit. Because MMSEV remains at the NEA, it is not available for safe haven use during the return voyage. It was also assumed that the DSH would resupply depleted consumables such as oxygen, water, or power to MMSEV between sorties, and to Orion prior to crew Earth return.

III.II EVA Operations

The DSH was not assumed to support nominal EVA. The MMSEV is optimized to support EVA exploration, and the Orion MPCV has emergency capabilities to survive cabin leaks for at least a short time. The DSH was expected to support contingency EVAs, since the MMSEV is not always present, and the Orion MPCV cannot support Primary Life Support System (PLSS)-based EVAs that require operating outside the immediate vicinity of the Orion module.

III.III Consumables

Because it was impractical to carry the mass of all water and oxygen needed for such a long mission duration, it was assumed that regenerative life support technologies would be employed.

IV. ISSUES AND DESIGN DRIVERS

The conceptual design process identified a number of interesting issues, some of which could become significant design drivers in a detailed DSH design.

IV.I Equipment Life Issues

Unlike the International Space Station (ISS), DSH will not have the luxury of regular resupply deliveries, meaning it must launch with everything needed for the 1,205 day total mission duration. Limited life consumables, such as food, may require special packaging. Mass and volume limitations will force the crew to disassemble equipment to make internal repairs—no easy feat in microgravity—rather than simply reach for a large replacement unit. The 825 day initial unmanned loiter period will also require remote vehicle health monitoring and spares already installed in parallel for critical systems

IV.II Design to Minimize Crew Radiation Exposure

One key issue for a long-duration mission is crew health risk due to Galactic Cosmic Ray (GCR) and Solar Particle Event (SPE) exposure. Unfortunately, all three methods typically used for radiation protection[1] are difficult to implement in a DSH mission: 1) Crew exposure time cannot be limited until new propulsion technologies are able to reduce transit time; 2) in the confines of a small spaceship on a mission beyond Earth's protective magnetic field, there are limited options for moving the crew away from the radiation source; and 3) the habitat's size and mass constraints limit the practical thickness of radiation shielding that can be carried.

Under the circumstances, the team incorporated design features to provide as much protection as reasonably possible. Assuming that a short, squat cylinder would enable the crew to move farther from the walls than a long, thin cylinder would, the DSH shell was set at 7 m (22.9 ft) diameter, the maximum that would fit within the launch shroud dynamic envelope (allowing for external micrometeoroid shields, cabling, and radiators). Stowage for food, clothing, and equipment was designated along the outer diameter (Figure 2), between the crew and the shell, providing some lateral radiation protection. It was assumed that the architecture elements mounted above and below the DSH would provide some axial shielding. Although practical for radiation protection, this approach has other design implications. For example, stowage located against the shell wall must be moveable in the event the crew must access the shell for repairs due to a micrometeoroid impact.

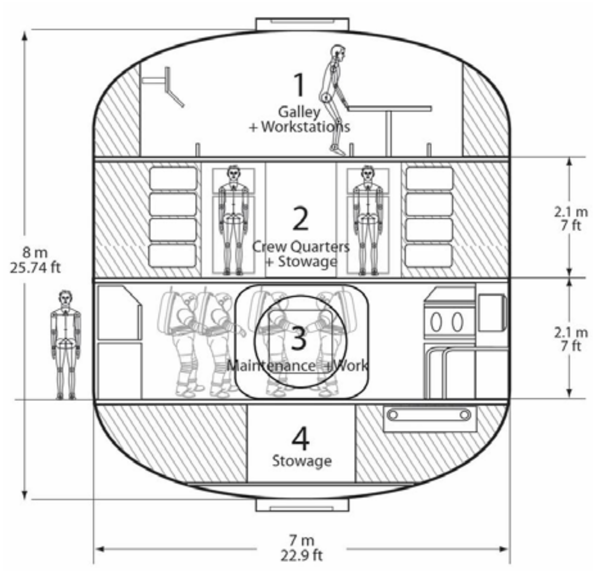

Fig. 2: Shaded areas represent stowage, which is used as crew radiation protection

Four individual crew quarters were positioned together at the center of the module, surrounded by a 10 cm thick integrated "water wall" radiation shield (Figure 3). Although this exercise stopped short of detailed design, several different implementation schemes were discussed. One interesting design incorporated portable water bags which could be reconfigured as needed, allowing the entire water wall to be collapsed into a smaller—but thicker--radiation shelter in the event of a particularly strong solar storm.

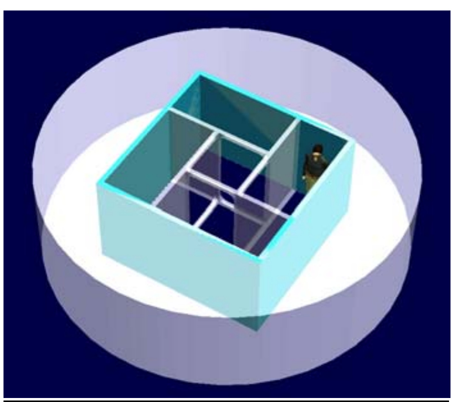
Fig. 3: "Water Wall" around crew quarters

Because the conceptual water wall carries 2,650 kg (5,842 lbs) of water, it is tempting to imagine this water serving dual purposes, though that may result in a complicated water distribution and control system. Leakage of such a large quantity of water into the cabin also poses risks to the crew and spacecraft. Finally, to minimize the structural design impact of launching such a large mass positioned near the center of the module, it may be necessary to launch the water in a tank mounted closer to the structure's perimeter, and fill the water wall once the DSH is in orbit.

Note that water wall thickness (and mass) could change once the effectiveness of perimeter stowage at reducing crew radiation exposure is better established. However, this requires knowing precise materials of construction and equipment placement, which was not done for this study.

IV.III Docking System and Hatch Commonality

Operational constraints drove the DSH to include a total of four docking systems and three crew hatches: a docking port on one end for the SEP; a docking port and hatch on the opposite end for crew transfer to Orion; a docking port and hatch along the cylinder length for crew transfer to the MMSEV; and a docking port, hatch, and Airlock opposite the MMSEV docking port for contingency operations such as EVA repairs or emergency MMSEV docking. Ideally, all of these docking systems would be of a common design to simplify operations and reduce costs. But different architecture elements, designed at different times for different purposes, may not necessarily specify common equipment. For example, current MMSEV and Orion hatch designs perform well for their intended use in shirt-sleeve conditions but may be marginal for large crewmembers wearing pressurized spacesuits. This could force DSH to carry two different types of docking/hatch systems or result in a DSH mass penalty to carry an adapter and remote installation system to convert ports for contingency use, where pressure-suited translation is required.

How large must an EVA crew transfer hatch and tunnel be? The answer depends on the type of EVA suit used in the DSH. The minimum clearance of the current NASA Docking System (NDS) Standard[2], with the docking petals removed, is 0.81 m (32 in). Reduced gravity testing[3] performed at the NASA Johnson Space Center evaluated the reach, access, visibility and range of motion for two different spacesuit configurations inside a 0.81 m (32 in) diameter translation tunnel (Figure 4).


Fig. 4: Reduced gravity testing of hatch operation in 0.81 m (32 in) diameter transfer tunnel.

Test subjects were asked to simulate common hatch actuation motions, such as overhead wrist rotation and crank motions. While these tasks were generally found to be possible, testing showed that clearance was highly dependent on suit configuration, particularly protrusions on the back and chest, which has implications to future EVA suit designs.

In addition to crew translation, the contingency EVA hatch will also be used to bring damaged external equipment inside the spacecraft for repairs that may be too delicate for gloved hands. Any equipment requiring this type of repair must be sized to fit through the hatch.

Finally, some thought must be given to active versus passive docking mechanisms. The current NDS design can be implemented such that either side of the docking interface can serve as the active partner, though there is a significant mass penalty for this flexibility. At least one side of each docking interface must provide active capture—but which side? The design team assumed the worst-case of all DSH docking ports carrying the heavier, active mechanism, but mass could be reduced if the passive function were shifted to other elements.

IV.IV Internal Cabin Pressure Commonality

Once the MMSEV, Orion, and DSH modules are integrated together and the hatches between them opened, all three must operate at the same internal cabin pressure and appropriate oxygen concentration to ensure crew and vehicle safety, streamline operations, and preserve consumable gasses. Unfortunately, different vehicles having different primary purposes do not always share common internal pressure characteristics.

Vehicles such as the MMSEV—whose primary mission is to serve as an EVA platform—prefer a lower cabin pressure with higher oxygen concentration to quickly condition EVA crew members for space suit operations at pressures as low as 29.6 kPa (4.3 psia). A reduced pressure atmosphere is also critical for the successful use of suitports. For this reason, current MMSEV design concepts assume a 55.2 kPa (8 psia), 32% oxygen nominal cabin environment. Orion, on the other hand, is primarily intended as a short-duration transit vehicle with no planned EVAs, and therefore has no reason to operate at such reduced pressures. However, Orion may need to dock with the ISS, which operates close to Earth sea-level conditions of 14.7 psia and 21% oxygen. Currently, Orion intends to operate[4] with a cabin pressure set point between 65.5 kPa (9.5 psia) and 102.7 kPa (14.9 psia), and up to 30% oxygen concentration at pressures below 70.3 kPa (10.2 psia).

Ideally, all three vehicles would settle on a mutually agreeable operating pressure and concentration. Because Orion is not currently planning to operate above 30% oxygen concentration, this would drive MMSEV to higher pressures (and hence less efficient EVA operations) or it would require Orion to recertify for lower pressure set points and higher oxygen concentrations. If neither of these approaches were possible, then DSH would be forced to keep the hatch to one vehicle closed when the other was open, and adjust pressure as needed, which complicates operations and wastes consumable gasses.

For the purpose of this exercise, subsystem designers assumed 70.3 kPa (10.2 psia) nominal cabin operations across the integrated vehicle stack.

IV.V Structural Design Issues

The DSH team encountered a number of interesting structural design challenges, particularly with respect to launch and in-space maneuvering loads. To minimize mass, designers assumed composite-Aluminum honeycomb sandwich construction. Floors were designed to sit on rings with only vertical connectivity to minimize stress concentrations. DSH control mass was assumed to be 27,930 kg (61,575 lbs), with unallocated mass distributed evenly along the floors, within 2m (6.6 ft) from the pressure shell.

One particular area of concern was the effect of 5 g axial and 2 g lateral launch loads when most of the internal mass was supported by the large diameter floors. To prevent excessive stress and deformation of the floors, the analysis team recommended a central structural support, and two concepts were discussed (Figure 5): a vertical composite tube, or temporary suspension cables or tension rods that could be removed after launch.

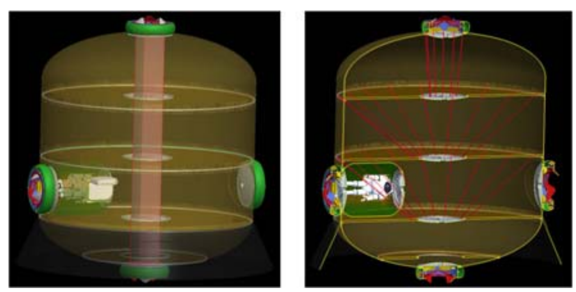

Fig. 5: Internal Structural Support Concepts

Launch loads were also a concern for both the internal airlock and the spacecraft adapter structure that connects the DSH to the rocket's upper stage. Securing the estimated 500 kg (1,102 lbs) airlock mass could likely be done with careful placement of the central structural support mentioned above. The spacecraft adapter structure was more problematic. A cone, rather than strut, adapter was selected, as it must be stiff enough to prevent excessive sway and low frequency issues, and providing lateral support via the launch shroud may not be economical. Structural analysis of the conceptual spacecraft adapter design indicated potential buckling load issues that should be addressed in future detailed design work.

Another area of concern was the 0.25 g axial in-space maneuvering loads with a 6,547 kg (14,434 lb) MMSEV attached at the DSH side docking port. Unless crew exercise equipment is isolated from the structure, fatigue may also be an issue.

To isolate smoke or contamination to one area, the Environmental Control and Life Support team suggested emergency covers on the passageways between the four DSH floors. However, the structural design team cautioned that making each floor a separate pressure compartment would result in a significant mass penalty. The compromise solution was to include sliding "pocket doors" between floors to aid in emergency response, but it was acknowledged that these doors would not allow selective depressurization of compartments.

IV.VI Pointing and Visibility

An inspection of the proposed architecture in Figure 1 shows that the large solar arrays on the SEP and Orion have high potential to interfere with line-of-sight pointing and visibility for DSH communications, tracking, guidance, and navigation equipment.

One possible solution to this problem is to extend navigation and communications equipment out onto long booms though this, in turn, may create new problems. Spacecraft vibration—such as that induced by crew physical exercise or during docking/undocking operations—could be transmitted along the booms, disrupting sensitive tracking equipment. Other problems include increased structural mass due to the booms, increased power distribution mass to reach extended equipment, and more complicated EVA repair and maintenance of equipment installed on booms.

The integrated vehicle configuration also posed design challenges for the Thermal design team. Although the large DSH shell provides ample area for body-mounted radiator panels, care must be taken to ensure the radiators are not shadowed by other elements, such as the MMSEV or SEP solar arrays.

Schedule constraints for this particular study did not allow consideration of alternative configurations or element designs, though those options should be considered for future studies.

IV.VII Water

Although current in-space water processing technologies with 90% or better recycling efficiency can dramatically reduce overall water mass carried on a long mission, one interesting question remains: how much water to start with? The answer depends largely on how much water is needed at any one time, and the worst-case repair scenario for a faulty water processor.

The Environmental Control and Life Support team estimated a crew of four would require a total of 5,374.1 kg (11,848 lbs) of life support water during a 380 day mission (Table 1), though only 11.6 kg (25.6 lbs) of potable water would be needed on any given day. Metabolic consumption, including crew exercise, was estimated using human-systems integration requirements developed by the Constellation Program. Life support water depleted from Orion and MMSEV, and resupplied by DSH, is also included in Table 1.

Potable Water	**Mass (kg)**
Deep Space Habitat	
• †Metabolic Consumption	3880.0
• Hygiene	620.8
• Contingency	411.1
MMSEV	
• ‡Tank Top Off (4 Sorties)	84.8
Orion MPCV	
• Tank Top Off (10 day return)	123.0
TOTAL (kg)	**5374.1**

Table 1: Life Support Water Required for a 4 Crew, 380 Day Mission.

Because only a small amount of potable water must be on hand at any given time, a relatively modest water tank paired with a high efficiency processor could reduce the mass of water launched from Earth by thousands of kilograms, depending on water processor efficiency and the number of contingency supply days required. It was estimated that a crew of 4 would need on average about 12 kg (26.5 lb) of water per day. Water for recharging the MMSEV must be delivered quickly, and should also be stored in a tank since generating from wastewater on demand may take too long. As noted above, an additional 2,650 kg (5,842 lbs) of water was required for crew radiation protection, in the form of a 10 cm-thick water "wall" surrounding the sleeping quarters. Unlike crew hygiene and hydration water, radiation shield water would not be recycled if it remained stagnant in the water wall.

IV.VIII Communication Challenges

Because the spacecraft will be as much as 0.33 Astronomical Units (AU) from mission control, the one-way light-time communication latency will be on the order of 165 seconds. This is much longer than the one-way 1.35 second latency between Earth and the Apollo crews who landed on the Moon, and raises interesting questions about the communication strategy between DSH and Earth. Unlike current ISS crews who are accustomed to near real-time guidance from mission control, the latency issue will likely require greater crew autonomy and decision-making. Alternatives to real-time voice communication such as texting, e-mail, and

† Estimated using NASA CxP 70024[5].

‡ Includes metabolic consumption and Extravehicular Activity (EVA) resupply.

voice messaging may also be more widely employed in a DSH mission.

In addition to the latency problem, the distance between DSH and Earth also increases the amount of radiated power required in conjunction with a high gain antenna for higher data rates to overcome signal losses. With current efficiencies of only 33%, this means that a 40 Watt Radio Frequency (RF) output would require 120 Watt power input, which potentially impacts both the power and thermal subsystem designs.

Although optical communication is a promising technology, it is not yet mature enough to overcome pointing inaccuracy risks, particularly on a distant spacecraft subject to crew-induced vibration. In order to transmit high resolution imagery, the DSH team selected a Ka-Band system for its superior data rate capability of up to 50 Megabits Per Second (Mbps), depending on distance, antenna size and amplification available. However, because Ka-Band can be disrupted by inclement weather on Earth, designers also recommended a secondary X-Band system. Although X-band transmissions may be as slow as 18 Kilobits per Second (kbps), it is a reliable backup or supplement to a primary Ka-Band system.

IV.IX Electrical Power and Distribution

Cable mass for a spacecraft as large and complex as DSH can become an issue without careful design consideration. The DSH Avionics team set a design goal of no more than 3.05 m (10 ft) length for any given wire harness. Locating control systems close to interfacing effectors and sensors, and specifying passive wireless external temperature and pressure sensors helped to minimize estimated cable mass.

For the purpose of this exercise, it was assumed that each module would produce the power required to operate independently. This may not be practical given a particular integrated vehicle configuration, but because mating elements are intended for use in other integrated configurations, bound for other destinations, this exercise did not include the integrated power load assessments that would be required in a more detailed design effort.

IV.X Contingency Scenarios

Discussion of worst-case contingency scenarios yielded a number of interesting design drivers. For example, the possibility of a crew fatality on a mission so far from Earth was found to affect the ECLS design. In-cabin fire or toxic chemical release scenarios prompted discussion of Orion safe haven placement within the vehicle stack, whether the floors within the module should be open to air flow or individual pressure compartments, and where to locate high risk items, such as high pressure oxygen equipment.

Although most contingency scenarios were deemed relatively low probability or fairly straightforward to mitigate, DSH decompression due to micrometeoroid penetration of the shell posed a number of challenges on such a long-duration mission. The DSH team assumed that a leak detection and repair kit would be manifested (similar to that currently carried on board the International Space Station) but it was noted that the leak repair method could drive shell material selection and construction decisions. Shell repairs made from outside the vehicle could pose hazards to an EVA repair crew, such as contamination from leaking fluid lines, electrocution, or glove punctures due to the jagged edges of damaged equipment. Ideally, repairs would be made from inside the vehicle, but this would require rapid relocation of stowage along the damaged wall, which would drive stowage system design. In the event of a large leak, the crew could be forced to perform repairs wearing protective pressure suits. Working inside the vehicle while wearing EVA suits would be cumbersome and difficult in some locations; the smaller launch/entry suits would be preferred, but it was noted that specially designed gloves would be needed to handle repair tools, and longer life support umbilical hoses may be needed to reach remote areas of the cabin. One strategy discussed was to perform a gross leak repair from inside the cabin to slow the leak, then follow up with an EVA repair once the situation is stabilized.

The DSH team discussed options in the event a leak cannot be repaired. As a last resort, the crew could permanently retreat to Orion, though this would be extremely challenging, particularly if the failure occurred early in the mission. This contingency would also require pre-planning to ensure long life support umbilical hoses were available for suited crew to periodically retrieve food and water from DSH, and empty the waste containment system, In this last resort scenario, the DSH water processor would have to be capable of operating in a vacuum, and the crew must be able to control the vehicle stack from Orion. It was also noted that the radiation protection “water wall” would freeze if the DSH depressurizes. Because of the myriad complications resulting from cabin depressurization, the DSH team concluded that robust micrometeoroid protection would be a wise investment. Although this exercise stopped short of a detailed shield design, one interesting concept proposed exploring the synergy between radiator panels and micrometeoroid shields.

V. APPLICABILITY TO OTHER SPACECRAFT

Although the particular transit vehicle discussed in this paper was developed around an asteroid mission, the exercise provides important insights into the design of a long-duration, deep space habitation module. Many of the issues identified here would be equally applicable to a manned Mars transit vehicle, for example, or even future space stations.

[1] Zapp, Neal, Space Radiation Protection Status and Challenges, Biennial Research Report, NASA Johnson Space Center, 2009.

[2] NASA, JSC-65795 Revision F, NASA Docking System (NDS) Interface Definitions Document (IDD), National Aeronautics and Space Administration, Houston, 2011.

[3] NASA, JSC-47223, ESPO Test 6: C9 Facility Space Suit Interface Evaluation Test Report, National Aeronautics and Space Administration, Houston, 2009.

[4] CxP 70000, Constellation Architecture Requirements Document, National Aeronautics and Space Administration, Houston, 2010.

[5] CxP 70024, Human-Systems Integration Requirements (HSIR), Appendix E, Revision E, National Aeronautics and Space Administration, November 19, 2010.