Space Launch System Co-Manifested Payload Options For Habitation

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The Space Launch System (SLS) has a co-manifested payload capability that will grow over time as the launch vehicle matures and planned upgrades are implemented. The final configuration is planned to be capable of inserting a payload greater than 10 metric tons (mt) into a trans-lunar injection trajectory along with the crew in the Orion capsule and its service module. The co-manifested payload is located below the Orion and its service module in a 10 m high fairing similar to the way the Saturn launch vehicle carried the lunar lander below the Apollo command and service modules. Various approaches that utilize this co-manifested payload capability to build up infrastructure in deep space have been explored in support of future asteroid, lunar, and Mars mission scenarios. This paper reports on the findings of the Advanced Concepts Office study team at NASA Marshall Space Flight Center (MSFC) working with the Advanced Exploration Systems Program on the Exploration Augmentation Module Project. It includes some of the possible options for habitation in the co-manifested payload volume of the SLS. Findings include a set of module designs that can be developed in 10 mt increments to support these co-manifested payload missions along with a comparison of this approach to a large-module payload flight configuration for the SLS.

I. Introduction

THE initial destination for the missions under consideration in this study was a lunar distant retrograde orbit (LDRO) that passes through or near the Earth-Moon Lagrangian points: L1 and L2. The LDRO is a stable orbit that is ideal for the asteroid retrieval mission[1] (ARM), suitable for Mars transfer vehicle assembly, fit for Mars habitat refurbishment between missions, and supportive of commercial and international interests in lunar missions. A location and implementation strategy with this kind of flexibility offers opportunities for reusability that have not always been practical from staging points at other locations.

The initial plan for the co-manifested payload on SLS is to provide an augmentation module that will extend the Orion's life support system for a crew of four from 21 days up to 60 days. With additional habitable volume in the augmentation module, it is envisioned that laboratory space can be outfitted to begin research, development, and testing of systems in deep space that are critical for long-duration exploration missions. This includes advanced vehicle systems, human healthcare research, deep space mission operations, and technology development.

With the planned arrival of an asteroid retrieval vehicle (ARV) in the mid-2020s, there will be a need to build up the LDRO facility and expand its exploration habitation systems. This expansion will include an airlock for crew extra-vehicular activity (EVA), robotic systems for assisting the EVA crew in collecting samples, and in-situ resource utilization (ISRU) experiments.

Mars mission planning includes a transit habitat in the 2030s that can accommodate a crew of four for up to 1000 days. Habitats within the 10 metric ton (mt) co-manifested payload limit were found to be too small for the Mars transit mission, so emphasis was placed on providing maximum volume with minimal systems onboard that could accommodate outfitting on later flights. Multiple modules were required in the design and then compared to a single module concept for overall mass, volume, and launch requirements.

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II. Space Launch System Configurations

The basic ground rules for the study included the usage of two Space Launch System (SLS) universal stage adapters (USA): USA2 and USA3, to provide a 10 m long payload bay and an assumed 10 mt payload capability on an SLS 1b launch vehicle configuration. Two concepts were developed to package the modules utilizing these adapters. The 10 m high payload bay and 10 mt payload capacity were set as assumptions for study purposes only, noting that current SLS capabilities are still in motion.

Figure 1 illustrates the two SLS configurations utilized for co-manifested payloads. The SLS 1b / USA2 configuration was used for Configuration 1 to package an International Space Station (ISS) 4.5m diameter habitat module inside the fairing. The SLS 1b / USA3 configuration was used to develop a new 5.5 m diameter habitat module that was integral to the 5.5 m cylindrical section of the USA3. For that configuration, the pressure vessel carried the launch loads using an aft USA1 conical section and a forward skirt connected to the Orion payload adapter.

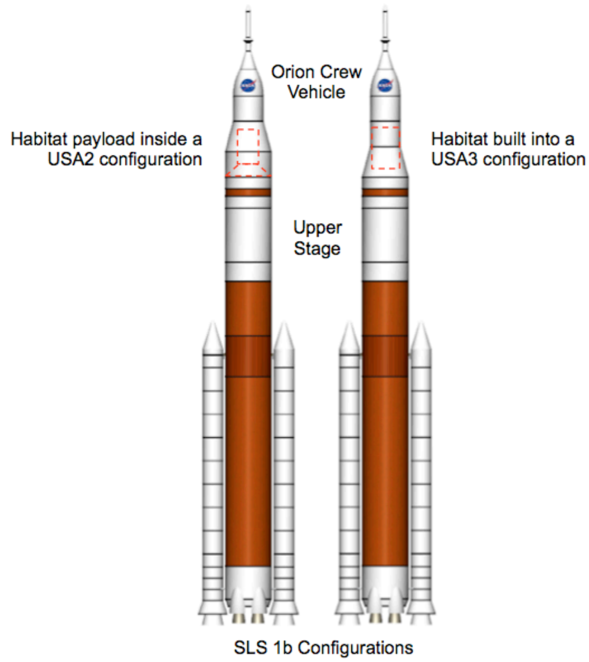

Figure 1. SLS 1b Configurations. *The USA2 and USA3 provide a 10 m high payload envelope between the upper stage and the Orion crew vehicle.*

All major elements are launched co-manifested with the crew in the Orion. In each case, after the trans-lunar injection (TLI) burn, the Orion is released and turns around to dock to its payload using a NASA docking system (NDS) port to extract a module in the same way the Apollo Command Module extracted the lunar lander from the Saturn V upper stage (see Figure 2). The volume available in the adapter fairings is sufficient for the mounting of deployable arrays (not shown) on the side of the 4.5 m diameter modules and on the end dome skirt of the 5.5 m diameter modules. The separation and payload extraction sequence illustrated in Figure 2 is basically the same for all co-manifested elements for both Configuration 1 and Configuration 2 as follows:

- SLS 1b is launched using the core stage and attached solid rocket boosters.
- The exploration upper stage (EUS) delivers the Orion and its co-manifested payload through TLI.
- After the TLI burn, the Orion is released, turns around, and docks with the co-manifested payload.
- The payload adapter / fairing releases the payload, allowing the mated stack to transfer to the LDRO destination.

The stage adapter and forward skirt that support the Orion service module are released for disposal at an undetermined stage in this sequence. There are several possible options that would release the adapter into a safe disposal trajectory. However, this event was not studied in detail. The aft conical adapter supporting the payload requires opening petals and can mimic the design as needed for the USA2 with the Configuration 1 modules.

III. Build Sequence

Primary emphasis was placed on a build up sequence for supporting the asteroid retrieval mission, a 300-day Mars demonstration mission, and a final configuration that could be utilized for 1000-day Mars transit missions (see Figure 3). Commercial participation was assumed to include logistics support. Additional commercial and international participation was acknowledged for possible lunar missions per current Global Exploraton Roadmap[2] planning, but was not investigated in any detail for this study. Build up tasks included the development of two basic configurations as noted. Five variations of Configuration 1 were examined to investigate the build up sequence and two variations of Configuration 2 were examined to investigate further the final Mars vehicle configurations.

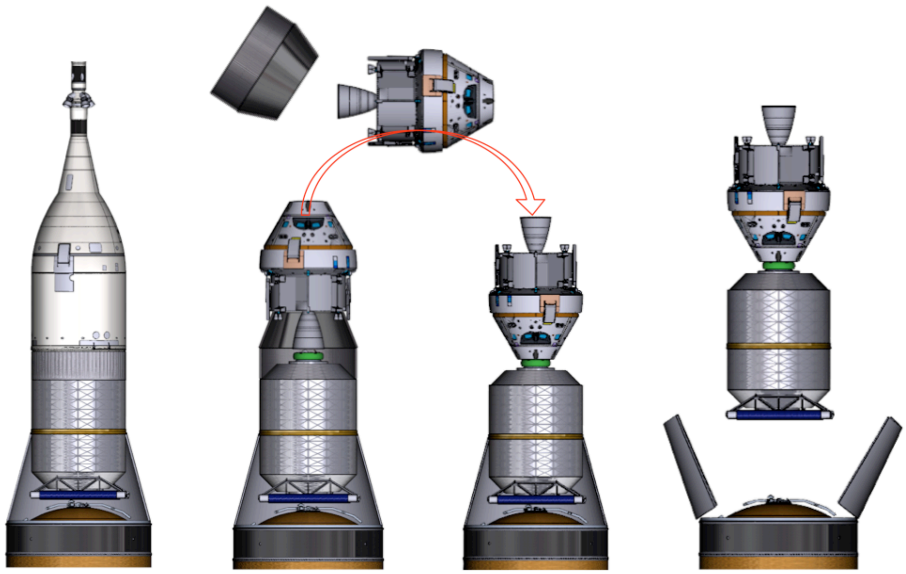

Figure 2. Co-Manifested Payload Extraction Sequence. *The co-manifested payload illustrated above is from Configuration 2 for a 5.5 m diameter module that is integrally built to the USA3 profile. After the TLI burn, the Orion is released, turns around, and docks to the payload, extracting it from the remaining fairing or adapter.*

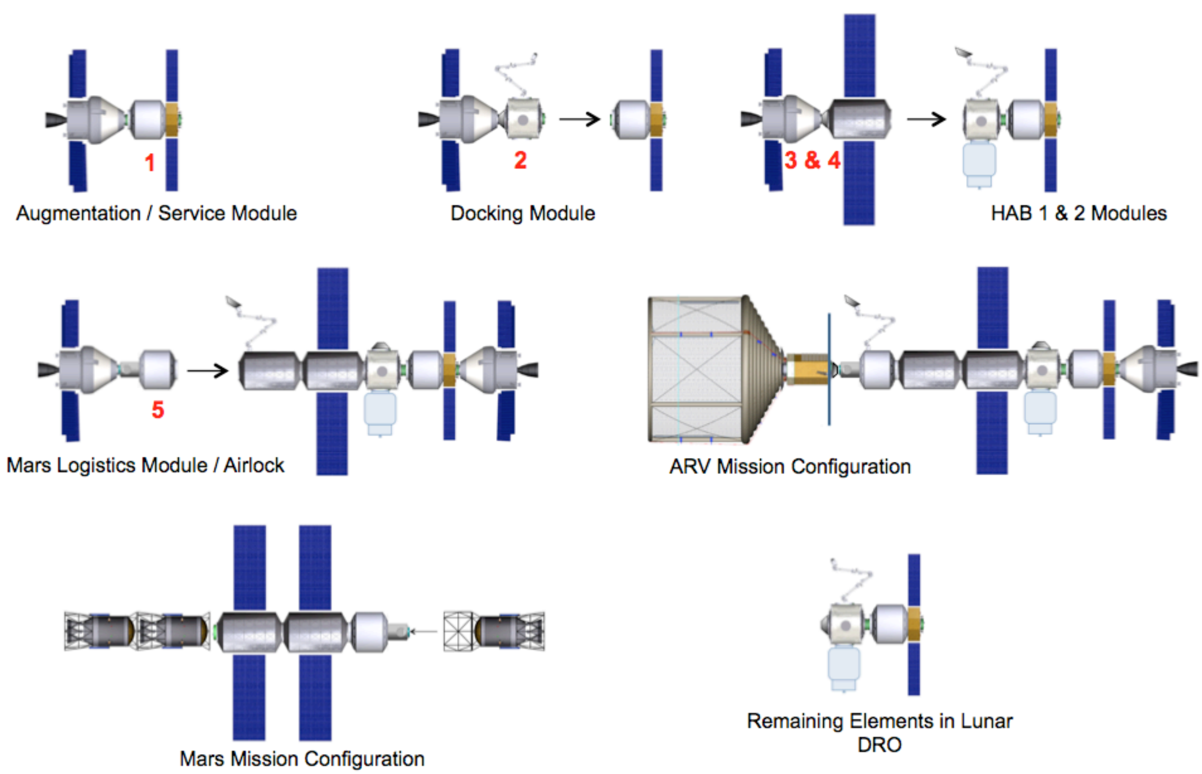

Figure 3. Build Up Sequence. *The build sequence for Configuration 1 using ISS diameter modules required five SLS 1b launches using the USA2. The build sequence for Configuration 2 using a larger 5.5 m diameter module is the same except that element 5, the Mars Logistics Module, is not required.*

The build sequence development defined a Service Module with docking ports at each end for the first element and a Docking Module with EVA capability as the second element. Two Habitat (HAB) Modules were needed to meet the total volume requirements for packaging all support systems and followed as the third and fourth elements in the build sequence. A fifth element was required for Configuration 1 to accommodate the large volume of Mars mission logistics and provide additional habitable volume for the crew. Once attached to the vehicle stack, the vehicle is suitable for the 300-day demonstration and ARV attachment.

The Mars mission configuration requires only the two habitat modules and logistics module. The concept is to attach these elements to the trans-Mars injection (TMI) and Mars orbital insertion (MOI) stages to complete the Mars mission configuration. Some current mission concepts for Mars use a pre-deployed trans-Earth injection (TEI) stage for the return of crew and habitat to Earth orbit. This plan is illustrated in Figure 3.

Note that during the build up, only one set of solar arrays is deployed from one habitat module until the Mars mission configuration is deployed. Since all the habitat arrays are sized for the Mars mission, they are oversized for the LDRO mission. As a result, only one array set is required to support the entire vehicle while in LDRO and the other set can remain stowed until needed for the Mars transit mission. Once the Mars vehicle is deployed, the only elements remaining in LDRO are the Docking and Service Modules. These elements are utilized to facilitate refurbishment of the habitat modules upon their return from Mars and support other possible commercial and international activities.

IV. Configuration 1

The first element in the build sequence is the Service Module (Figure 4), which augments the Orion by providing additional volume and logistics to support four crewmembers for 30-60 days and provide overall propulsion and control in LDRO. Though not specified, each co-manifested module acts as an augmentation module during delivery from TLI to LDRO. Acting as an augmentation adds functionality for crew access to the additional habitable volume, crew exercise equipment, additional food, logistics, research equipment, and an open loop environmental control and life support system (ECLSS) to supplement the Orion's capabilities. Although the multiple open-loop systems added significant redundancy, they also added significant overall mass to the co-manifested configuration.

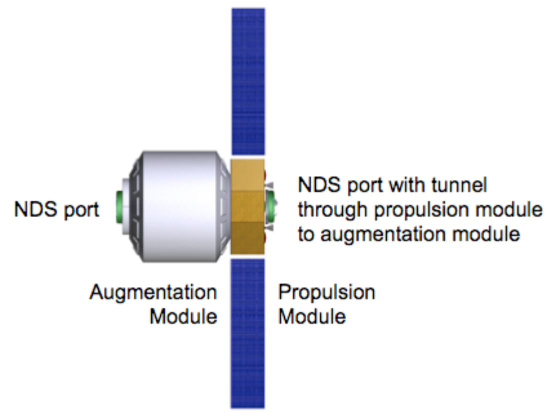

Figure 4. Service Module. *The Service Module provides pressurized volume to augment the Orion capabilities and a propulsion module to provide control of the final vehicle configuration in LDRO.*

The Service Module has a 30 in round NDS port at each end with a tunnel through the propulsion section for crew access to the larger volume. The initial design had only one docking port, which complicated the build process by requiring the relocation of the module to radial ports at times. An additional docking port alleviated this problem. The propulsion module provides:

- A stable platform with attitude control
- Translation in the positive X direction
- A stable, cooperative, and passive docking target

The propulsion system leverages high heritage flight hardware from existing flight systems utilizing a storable, bipropellant combination of nitrogen tetroxide (NTO) oxidizer and monomethyl hydrazine (MMH) fuel. The propulsion module was not designed specifically for propellant servicing but could possibly accommodate this feature in the future. The propulsion and control systems are designed to control the stack

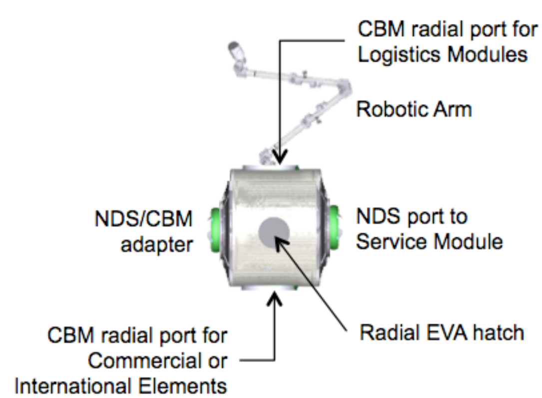

Figure 5. Docking Module. *The Docking Module provides EVA and robotic capabilities with both NDS and CBM ports.*

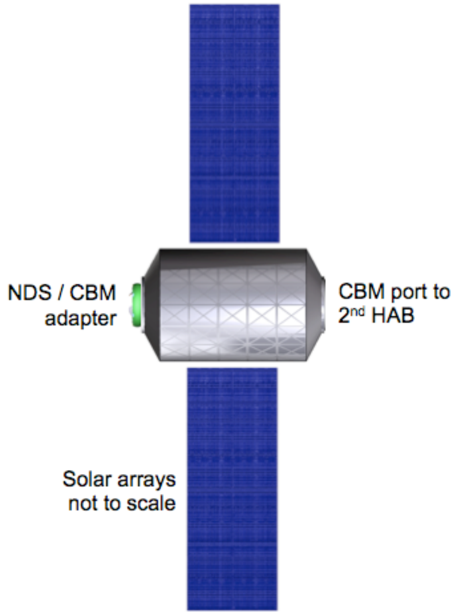

Figure 6. Configuration 1 Habitat Modules. *There are two 4.5 m diameter habitat modules and a logistics module designed to provide the volume required for four crewmembers to live and work on a 1000-day mission to Mars.*

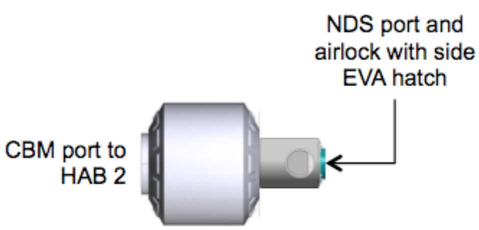

Figure 7. Mars Logistics Module. *The logistics module provides most of the consumables required for the 1000-day Mars transit mission and includes an airlock with EVA capabilities.*

during build up and provide some maneuvering for rendezvous with the ARV. An alternate design with larger tanks, which could provide transfer of the entire stack across the lunar DRO for rendezvous with the ARV, was examined. The baseline design has about half that capacity. The same propulsion system is also suitable for an expendable launch vehicle (ELV) element attached to a logistics module.

The Docking Module (Figure 5) is the second element to be launched. Several configurations considered putting it in place at a later point in the build sequence. This placement configuration further complicated the build process, however. The docking module has a radial EVA hatch and can be used as an airlock. There are two end ports, one with a NDS that accommodates a 30 in hatch and the other with a common berthing mechanism (CBM) that accommodates a 50 in hatch. The NDS port is used to dock to the Service Module, and the CBM port is used to berth with the first Habitat Module. Two additional CBM ports are provided in radial positions, with room for a third opposite the EVA hatch if mass allocation permits. Since the Orion uses a NDS port during transfer from TLI to LDRO, the Docking Module and the two Habitat Modules require a CBM/NDS adapter on the CBM end port where the Orion attaches. The adapter is a short version of the pressurized mating adapter (PMA) on the ISS. A robotic arm is included to assist with berthing operations, EVA activities, and relocation of adapters during the build process.

There are two Habitat Modules (Figure 6) based on the ISS multi-purpose logistics module (MPLM) also known as the pressurized logistics module (PLM). The modules are longer by about one ISS Payload Rack (ISPR) width, or about 7.2 m x 4.5 m in diameter each. All the modules in Configuration 1 are the same diameter based on the MPLM design. HAB 1 contains a regenerative ECLSS for the entire vehicle, so the common berthing mechanism (CBM) ports with a 50 inch square hatch are required to accommodate outfitting and passthrough of air, fluids, power, and data services. Accommodations in HAB 1 include two crew quarters, an exercise area, medical equipment, mission equipment, storage, and a waste management and hygiene compartment. HAB 2 contains the other two crew quarters, an open wardroom area with galley equipment, additional mission equipment, and storage. Details on internal packaging can be found in previous ISS derived deep space habitat technical papers.[3]

HAB 1 fit within the 10 mt budget only by removing almost all of the internal outfitting, requiring most internal systems to be modular for delivery on logistics flights. Open loop ECLSS consumables are included to support the Orion crew for 60 days while they install the closed loop ECLSS system in HAB 1. HAB 2 fits within the 10 mt budget but also requires logistics flights and significant on-orbit assembly.

The Mars Logistics Module (Figure 7) is the last major element in the stack and contains volume for storage of consumables, spares required for long duration missions, and an airlock. It fits within the 10 mt mass budget and can include about 4 mt of logistics. The layout has a central aisleway connecting the habitat to the airlock. The space between the aisleway and pressure vessel wall is dedicated to packaged logistics.

V. Configuration 2

Configuration 2 uses two HAB modules that are larger in diameter to fit the SLS USA3 launch configuration discussed in Section II above. The overall build sequence is the same as Configuration 1, except that the Mars Logistics Module is not required. The two HAB modules are larger in diameter at 5.5 m each and provide sufficient volume to include Mars logistics. The module lengths were maximized to fit within the available 10 m height of the USA3 profile between the aft EUS and the forward Orion and service module (Figure 2).

A structural support ring transfers launch loads from the cylindrical section of the pressure vessel to a conical USA1 launch adapter. The pressure vessel surface area above the structural ring is exposed to the launch environment and is covered with multilayer insulation (MLI) and an aeroshell. The pressure vessel surface area below the structural ring is covered with MLI and a micrometeoroid debris protection system (MDPS). Solar arrays on the HAB modules are shown in their stowed position inside the fairing in Figure 2 and their deployed position in Figure 8. Surface-mounted radiators were sized but are not shown in the graphics.

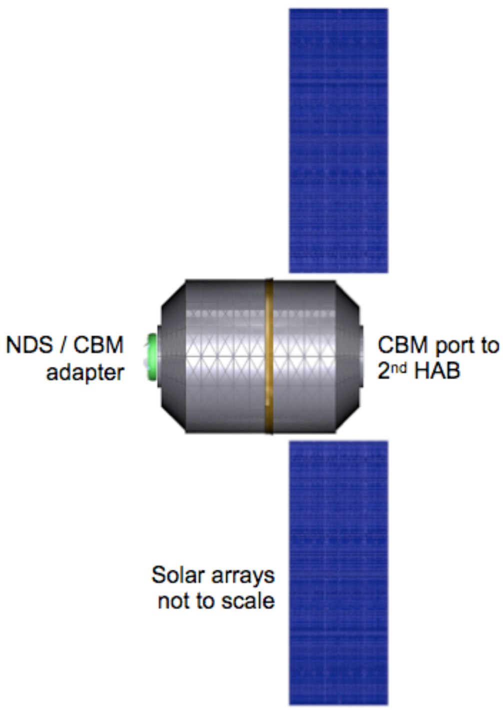

Figure 8. Configuration 2 Habitat Module. *There are two 5.5 m diameter habitat modules designed to provide the volume required for four crewmembers to live and work on a 1000-day mission to Mars.*

Deck spacing was an important aspect governing the internal layout. All concepts used a 2 m "floor to ceiling" spacing to accommodate a 95-percentile male neutral body posture. The 5.5 m diameter allowed two possible deck orientations to capture the best use of the volume. Both were studied and a horizontal layout was selected, which ran a central structural deck along the centerline length of the barrel, dividing the diameter into two deck levels. This permitted a more efficient packaging layout along the barrel section walls and utilized the end domes for translation between decks.

The ground rule set for Configuration 1 was a 10 mt payload capability for both the payload inside the USA2 adapter/fairing and its supporting payload adapter. Given that ground rule, a fair comparison considered that Configuration 2 only uses the lighter conical section of the USA3 (the USA1), resulting in an additional 1.7 mt mass that could be added to the payload to yield an 11.7 mt mass limit.

For Configuration 2, HAB 1 exceeded the initial 10 mt budget but fit within the modified 11.7 mt budget by removing almost all of the internal outfitting for delivery on logistics flights as required for Configuration 1. Open loop ECLSS consumables were included to support the crew with the Orion for 60 days while they install the closed loop ECLSS system.

HAB 2 also exceeded the 10 mt budget but fit within the modified 11.7 mt budget by removing almost all of the internal outfitting for delivery on logistics flights. The distribution of internal outfitting was the same for each module as described for Configuration 1, except that they were distributed on two deck levels in each module and have additional stowage volume.

VI. Vehicle Subsystems

Configurations 1 and 2 were sized using the same subsystems but reconfigured to work with the different layouts. In most cases, there are only minor differences in the subsystem mass between the two configurations. The power system is designed to function in both LDRO and Mars orbit. The solar illumination at Mars is about 40% of that at LDRO. To compensate, the HAB arrays are sized for Mars illumination, which means in LDRO, just one set of the HAB arrays will be more than enough to power both HAB modules. As a result, the arrays for HAB 1 are used while the vehicle is in LDRO and the second set of arrays on HAB 2 are not deployed until required for the Mar transit mission. The avionics system is derived from Orion for maximum compatibility. Each HAB module has control authority that is complimentary with the Orion to control the Service Module during the asteroid mission and the 300-day Mars mission demonstration as well as the propulsion stages for the Mars transit mission. The thermal system is similar to the ISS with shell heaters, MLI on the outside shell protected by a micro-meteoroid and orbital debris (MMOD) shield, and a fluid loop to feed internal heat to external body-mounted radiators. The ECLSS is also ISS derived, with systems for air and water purification, and spares and consumables sized for the mission based on ISS experience, and near-term expected advances. Radiation protection is included around the crew quarthers for solar proton events (SPE) in the form of polyethylene panels forming a storm shelter for anticipated short random events.[4]

VII. Launch Sequence Comparison

A launch sequence comparison is shown in Figure 9 between the three small modules from Configuration 1, the two medium modules from Configuration 2, and a new single large module habitat configuration from an earlier study.[5] Both SLS utilization flights (UL) and supporting ELV logistics flights (LF) are shown indicating the number of 10 mt elements and 4 mt outfitting flights required for each approach. For simplification, the build up reaches an end state for the Mars transit mission scenario and excludes the various logistic requirements for the asteroid mission and 300-day demonstration mission. For each of the three scenarios, UL-1 delivers a Service Module as a co-manifested element with the crew and UL-2 delivers a Docking Module. The UL-2 flight is joined by the LF-1 logistics flight from an ELV, which delivers additional research equipment and a robotic arm if that element cannot be included within the 10 mt limit on the UL-2 flight. Each logistics flight is assumed to carry 4 mt each, and from here, each of the scenarios differ.

For the three small co-manifested modules from Configuration 1, UL-3 delivers HAB 1 and requires an additional 2.5 logistics flights (or 10 mt of outfitting) to complete the interior of the habitat. UL-4 delivers HAB 2 and requires an additional 1.5 logistics flights (or 6 mt of outfitting) to complete the interior. The difference in outfitting mass between the two HAB modules is primarily in the ECLSS for HAB 1. The Mars logistics module is delivered on UL-5, which can also support the ARV-1 asteroid mission. An assumed 13 mt of logistics are required for the Mars mission, which are supplied by two ELV flights with 8 mt and the 5 mt of logistics that can be co-manifested with the crew on the Mars-1 flight. In total, six SLS and seven ELV flights are required to reach a Mars transit configuration.

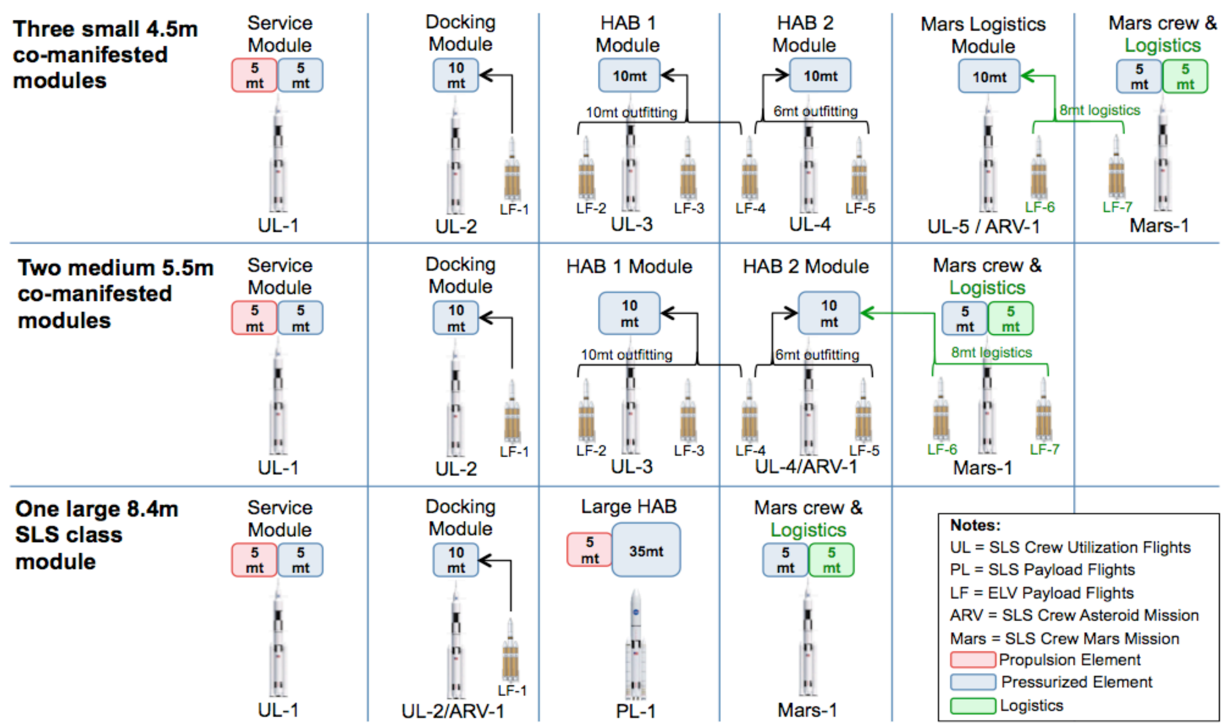

Figure 9. Launch Sequence Comparison. *The number of launches for the two co-manifested payload configurations are compared with the number of launches for a single large habitat in an SLS 1b Payload configuration.*

The two medium co-manifested modules from Configuration 2 are similar; except the larger volume modules can accommodate the Mars mission logistics to alleviate the need for a separate Mars Logistics Module. This does not change the number of logistics flights required. However, it does reduce the number of SLS flights from six to five to reach the Mars ready goal.

For comparison purposes, a single large module from a previous study[6] was placed on a payload flight (PL) and added to the manifest mix. The large module did not require outfitting or logistics flights to complete the interior configuration. This significantly reduced the number of ELV flights from seven to one, and the number of SLS flights down to three utilization flights and one payload flight for a total of four. After going through this exercise, significant savings can be seen in both the time and launch costs of a one large module payload flight.

VIII. Mass Summaries for Mars Vehicle Configurations

Figures 10 through 12 show the three Mars Vehicle configurations analyzed in this study. Each uses the same mission scenario showing attachment to the TMI and MOI stages for transfer to the TEI stage in Mars orbit. For comparison purposes, the mass requirements were normalized between the three configurations at the subsystems level to make a fair comparison of the three and two module sets with the single module concept from a previous study.

The Mars Vehicle derived from Configuration 1 is shown in Figure 10. It includes all of the outfitting required for HAB 1 and HAB 2, as well as the logistics required for the Mars Logistics Module to support a 4 crew/1000 day mission. The total mass of 52.4 mt exceeds current 40 mt goals[7, 8] by 12.4 mt and the habitable volume at 95m^3 is considered tight for a mission of this duration.

The Mars Vehicle derived from Configuration 2 is shown in Figure 11 and improves the habitable volume slightly at 120 m^3. The stowage volume is only slightly less than provided by Configuration 1 but appears to be adequate such that a separate logistics element is not required. The total mass of 47.8 mt is an improvement. However, it still exceeds the 40 mt goal by 7.8 mt.

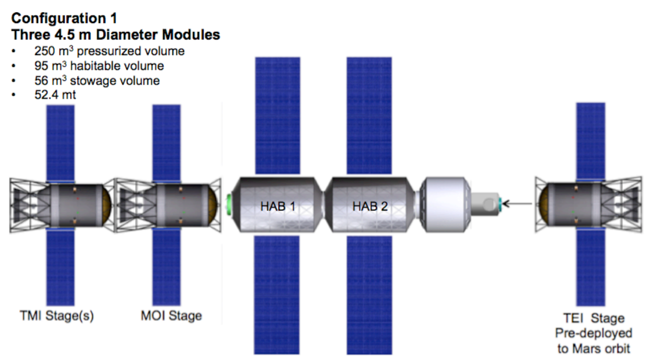

Figure 10. Configuration 1 Mars Vehicle. *This configuration uses two HAB modules and one Logistics Module that are derived from ISS elements, about 4.5 m in diameter.*

Finally, the Mars Vehicle derived from the single large module habitat provides a spacious 341 m^3 habitable volume for the crew (about three times the volume of the other two configurations). The mass of 44.8 mt still exceeds the 40 mt goal by 4.8 mt, but the trend is moving in the right direction. This suggests that single module approaches have merit from a mass perspective and warrant further study.

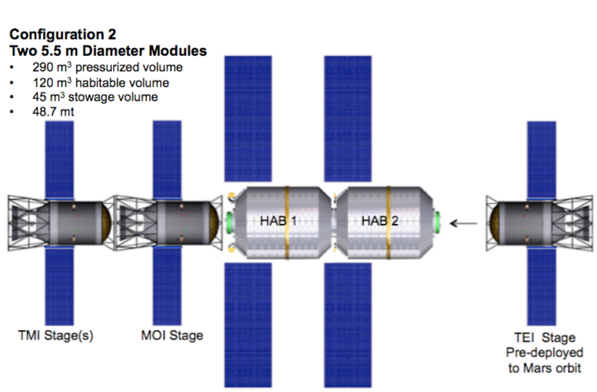

Figure 11. Configuration 2 Mars Vehicle. *This configuration uses two HAB modules that are 5.5 m in diameter to match the cylindrical section of the SLS USA3 payload adapter. It provides adequate volume such that an additional logistics module is not required.*

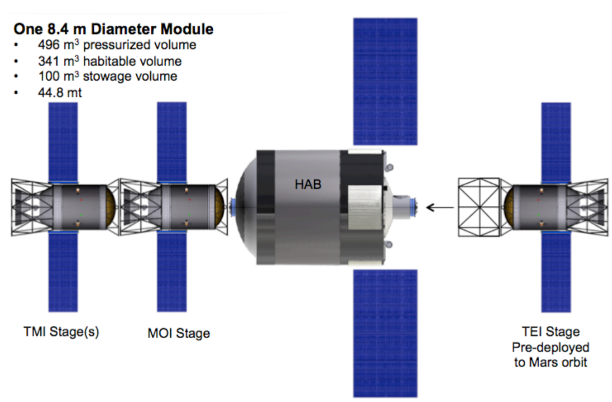

Figure 12. Configuration 3 Mars Vehicle. *This large single module configuration is 8.4 m in diameter matching the SLS core stage. It provides nearly three times the habitable volume of the other configurations with a lower total mass.*

Figure 13 provides another comparison with historical data of mass and volume trends.[9] The Skylab was a large single module habitat that provided about 555 m^3 of habitable volume for about 49 mt. This is comparative with the many modules on ISS where ten times the mass at 450 mt resulted in less habitable volume at 355 m^3. In examining the mass statements from the historical and new studies, it was found that the structural mass of the many connections and end domes between modules adds significantly to the total mass. In addition, there are many internal subsystems that are duplicated for each module when multiple modules are used. When these facts are considered in detail, it is easy to understand how volume can be increased and how mass can be reduced simply by reducing the number of individual elements.

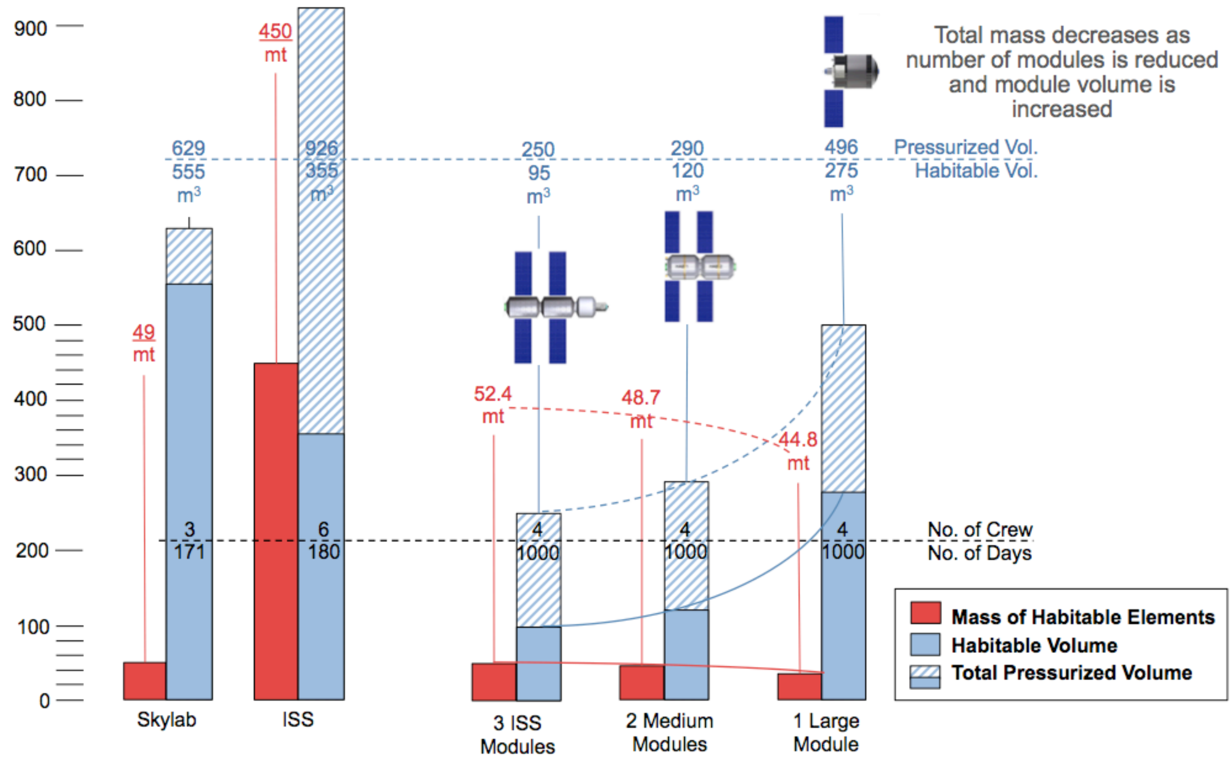

Figure 13. Mass and Volume Comparison. *The new configurations provide an interesting comparison with the Skylab and ISS historical data, showing that total volume can be increased and total mass reduced by simply reducing the number of individual elements.*

IX. Findings and Recommendations

Of the configurations examined in this paper, only the single large module configuration appeared to approach the 40 mt goal. Recommendations going forward included further investigation of additional single module configurations to further refine the right size for a Mars transit mission. Additional findings and recommendations included the following:

- **Configurations:** Decreasing the number of pressure vessels and increasing the pressure vessel diameter and volume can:
  - Reduce total mass for the Mars Vehicle configuration
  - Reduce the number of SLS flights
  - Reduce the number of outfitting flights
  - Reduce the overall build schedule
  - Significantly reduce on-orbit outfitting operations

- **Service Module:** The pressure vessel for the augmentation module in this design is probably oversized and can be reduced in volume resulting in mass savings. Two NDS docking ports with a pressurized tunnel through the propulsion module facilitated the build sequence and overall control of the stack.
- **Docking Module:** The Docking Module uses CBM ports and a robotic arm to facilitate:
    - Berthing of HAB elements
    - Logistics flights
    - Outfitting of the HAB modules
        - An additional CBM radial port could be added to this design and is recommended. The Robotic Arm may require delivery on a logistics flight due to mass limitations.
- **HAB Modules:** Large volume modules reduce the mass and number of flights required for the Mars mission.
    - HAB 1 contains regenerative ECLSS for both habitat modules.
    - Interconnects between habitat modules require CBM ports for air, water, and power passthroughs.
    - Independent ECLSS was investigated for each habitat module and found to double the system mass.
        - However, that feature may prove to reduce spares and provide additional redundancy.
    - The two module set, although more massive than the single volume habitat, did prove to have additional options for redundancy and safe haven development that may be difficult to produce in a single module design.
- **ECLSS:** An open loop ECLSS is provided on the Service Module, Docking Module, the two HAB modules, and the Mars Logistics Module, to facilitate use by the Orion crew during transit to the LDRO.
    - Hardware and consumables for the open loop systems on the first three elements prior to getting the regenerative ECLSS system operational totaled about 3.6 mt, which is more than the mass of the regenerative system hardware.
    - Consideration should be given to modifying the Orion ECLSS to service the extended duration flights without augmentation.

X. Conclusion

The most significant findings from this study indicate that with SLS, there is great value in pursuing large volume habitats. SLS offers a single launch solution that can put a space station facility in orbit — fully outfitted as was done with the original Skylab program — with no ongoing build up or outfitting flights as have been required by the Shuttle / ISS programs. In addition, it was found that there is significant mass savings by working toward larger modules and fewer module elements for Mars mission configurations. Issues like safe havens and the right size volume need to be addressed but the trend seems to lean toward the value of larger volume single element designs where possible.

Appendix A

Abbreviations & Acronyms

AES	Advanced Exploration Systems
ARM	Asteroid Retrieval Mission
ARV	Asteroid Retrieval Vehicle
A/SM	Augmentation / Service Module
CBM	Common Berthing Mechanism
DM	Docking Module
DRO	Distant Retrograde Orbit
EAM	Exploration Augmentation Module
ECLSS	Environmental Control & Life Support System
ELV	Expendable Launch Vehicle
EUS	Exploration Upper Stage
EVA	Extra-Vehicular Activity
HAB	Habitat
ISPR	International Space Station Payload Rack
ISRU	In-Situ Resource Utilization
ISS	International Space Station
kg	kilograms
L1	Lagrange Point 1
L2	Lagrange Point 2
LDRO	Lunar Distant Retrograde Orbit
LF	Logistics Flight
LM	Logistics Module
m	meter
MDPS	Micrometeoroid Debris Protection System
MLI	Multi-Layer Insulation

MMH	Monomethyl Hydrazine	NTO	Nitrogen Tetroxide
MMOD	Micro-Meteoroid and Orbital Debris	PL	Payload flight
MOI	Mars Orbital Insertion	PLM	Pressurized Logistics Module
MPLM	Multi-Purpose Logistics Module	PMA	Pressurized Mating Adapter
mt	metric tons (1000 kg)	SLS	Space Launch System
MPCV	Multi-Purpose Crew Transfer Vehicle (Orion)	SPE	Solar Proton Events
		TEI	Trans-Earth Injection
MSFC	Marshall Space Flight Center	TLI	Trans-Lunar Injection
NASA	National Aeronautics and Space Administration	TMI	Trans-Mars Injection
		UL	Utilization flight
NDS	NASA Docking System	USA	Universal Stage Adapter
No.	Number	Vol.	Volume

Acknowledgments

The study activities reported in this paper were supported primarily by the NASA Headquarters' Advanced Exploration Systems Program, through the Exploration Augmentation Module Project, managed by Lora Bailey at the NASA Johnson Space Center. Primary study participants from which this data was produced included Brand Griffin, Mike Baysinger, Jay Garcia, David Tabb, Leo Fabisinski, Don Biggs, Andrew Schnell, Tom Percy, Dan Thomas, Jack Chapman, and Alan Philips, through the Advanced Concepts Office at the NASA Marshall Space Flight Center.

References

[1]Brouphy, J., Culick, F., Friedman, L., "Asteroid Retrieval Feasibility Study," Keck Institute for Space Studies, Jet Propulsion Laboratory, Pasadena, CA, 2012.

[2]International Space Exploration Coordination Group, "Global Exploration Roadmap," NASA NP-2013-06-945-HQ, 2013.

[3]Smitherman, D., Russell, T., Griffin, B. N., et al, "Deep Space Habitat Configurations Based on International Space Station Systems," *Global Space Exploration Conference*, GLEX 2012.01.1.8x12219, Washington, DC, 2012.

[4]Cucinotta, F.A., Kim, M.Y., Chappell, L.J., "Evaluating Shielding Approaches to Reduce Space Radiation Cancer Risks," NASA TM-2012-217361, p.8, May 2012.

[5]Griffin, B. N., Smitherman, D., Kennedy, K. J., et al., "Skylab II: Making a Deep Space Habitat from a Space Launch System Propellant Tank," *AIAA Space 2012 Conference and Exposition*, AIAA 2012-5207, Pasadena, CA, 2012.

[6]Griffin, B. N., Smitherman, D., Howe, A. S., "Internal Layout for a Cis-Lunar Habitat," *AIAA Space 2013 Conference and Exposition*, AIAA 2013-5433, San Diego, CA, 2013.

[7]Drake, B., ed., "Human Exploration of Mars Design Reference Architecture 5.0," NASA SP-2009-566, 2009.

[8]Drake, B., ed., "Human Exploration of Mars Design Reference Architecture 5.0 Addendum," NASA SP-2009-566-ADD, 2009.

[9]Smitherman, D., Griffin, B.N., "Habitat Concepts for Deep Space Exploration," *AIAA Space 2014 Conference and Exposition*, AIAA 2014-4477, San Diego, CA, 2014.