Surface Transportation of the Common Habitat from Lander to Habitation Zone

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Abstract— **The Common Habitat Architecture is a feasibility study surrounding the use of an SLS core stage liquid oxygen tank as the pressure vessel for a long-duration habitat intended for use in multiple gravity environments. The Common Habitat is used within this study as the primary habitation element in both Moon and Mars surface base camps. The Common Habitat Architecture offloads the Common Habitat from its lander and transports it to a Habitation Zone instead of leaving the habitat integrated with the lander. In this study, the Landing Zone is assumed to be approximately 3.5 kilometers from the Habitation Zone. Given the physical size and estimated 90-ton mass of the Common Habitat, a four-week trade study encompassing Moon and Mars lander identification, offloading, surface transport, and emplacement was conducted in February 2021 to assess whether there are any credible options for landing the Common Habitat on the Moon or Mars and deliver it to its intended point of use. Constrained to use only public data, the study applied subject matter expert opinion to each component of the study. The surface transportation component of the trade study assumes the habitat has been successfully offloaded from its lander and is at a point of handover to the surface transportation system. It is assumed that there are no crew present, and all human operations are performed remotely by Mission Control personnel. Three core cargo handling elements from prior NASA studies were used as the basis from which to derive surface transportation options – the Chariot, the All-Terrain Hex-Limbed Extra-Terrestrial Explorer, and the Lightweight Surface Manipulator System. Variations and hybrid combinations of these elements were used to develop transportation options for the Moon and Mars, given different habitat masses. Ultimately, several potentially feasible solutions were identified, and a solution was recommended that is common to both the Moon and Mars, with the potential to use a dissimilar system as a backup during lunar Common Habitat delivery. Next steps for sizing and additional development and analysis of the recommended surface transportation system are included as forward work.**

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1. INTRODUCTION

Common Habitat Overview

The Common Habitat Architecture is an exploratory study focused on the use of a Skylab-like application of the Space Launch System (SLS) Core Stage Liquid Oxygen (LOX) tank, shown in Figure 1 and Figure 2, as the primary structure and pressure vessel for an eight-crew habitation element intended for long-duration missions with an internal architecture equally suitable for use in 0g, 1/6g, 3/8g, and 1g environments throughout the inner solar system. [1]

Figure 1. SLS LOX Tank

The habitat is outfitted in a horizontal, three-deck configuration with private functions on the lower deck, research, maintenance and exercise systems on the mid deck, and group functions, commanding, medical, and subsystems on the upper deck. [2]

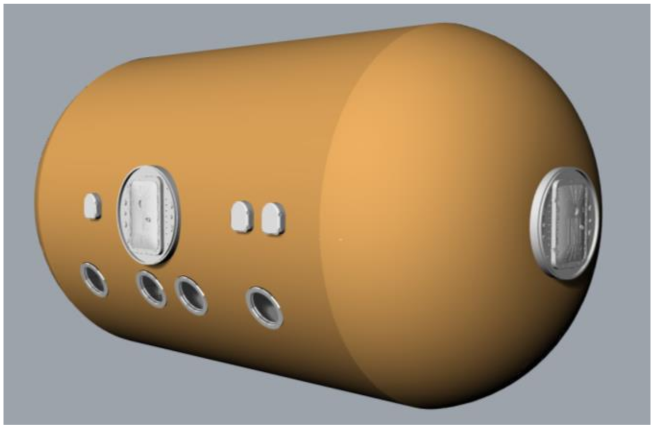

Figure 2. SLS LOX Tank as the Common Habitat

Within the Common Habitat Architecture, the Common Habitat is docked to other elements to form a habitable environment for its crew. On the surfaces of the Moon and Mars, the Common Habitat forms the core of a surface Habitation Zone [3], as shown in Figure 3. In microgravity, the Common Habitat is the primary living and working environment within the Deep Space Exploration Vehicle (DSEV) [4], shown in Figure 4.

Figure 3. Common Habitat Docked with Airlock, Logistics Modules, and Pressurized Rovers

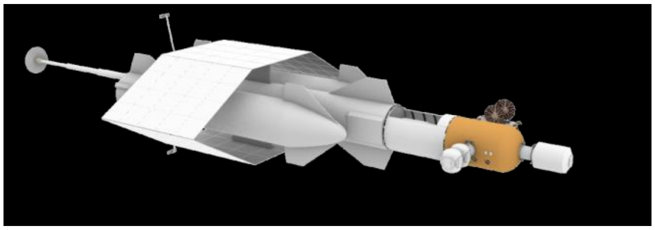

Figure 4. Common Habitat within the Deep Space Exploration Vehicle

The Common Habitat Architecture Study is a feasibility study and is not part of current NASA Moon to Mars mission planning and acquisitions. It is instead an ongoing study of potential options that – should viability be demonstrated – could potentially be applied to human exploration programs. 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.

The Common Habitat has a control mass of 90 tons, and it is evident that it is within the performance limits of emerging super heavy lift vehicles to deliver such a payload to Earth orbit. Thus, it is clear that orbital assembly techniques could be used to integrate the Common Habitat into the DSEV. However, it is less certain how such a habitat can be deployed to form surface habitation systems. A one-month trade study was conducted by the Common Habitat study team with a small number of volunteer subject matter experts to examine how the Common Habitat can be transferred from its launch vehicle to where it must be positioned on the surfaces of the Moon and Mars to form the surface emplacement shown in Figure 3.

Trade Study and Results Overview

This trade study was conducted in the form of four weekly brainstorming sessions over the course of one month. Each brainstorming session constituted one subordinate study.

Lander Study—The lander study considered five candidate lander systems for delivery of the Common Habitat to the surfaces of the Moon and Mars. The study recommended the use of a modified Starship, with the barrel section of its payload section stretched by roughly seven meters.

Offloading Study—The offloading study focused on the challenge of how to remove the Common Habitat from a Starship after landing, rotate it from vertical to horizontal, and lower it to the surface. The study was supplemented by a JSC-sponsored hackathon that considered the same question. Both studies ultimately recommended a deployable crane system.

Surface Transportation Study—The results of the surface transportation study are the subject of this paper.

Surface Emplacement Study—The surface emplacement study discussed how the Common Habitat should be positioned within a surface outpost. The study recommended placement of the habitat in a trench, both for purposes of stabilizing the habitat and to lower its docking ports to a level where logistics modules, pressurized rovers, and an external airlock can be aligned for docking.

Initial Condition for Surface Transportation Study

This study acknowledges that surface transportation of a Common Habitat is a challenging endeavor. The 90-ton control mass of the Common Habitat is the desired minimum mass capacity for the surface transportation system. However, in case such a transport proves unfeasible, lower masses of 30-tons and 50-tons are also considered in this study. These masses assume that some portion of the

Common Habitat mass is offloaded, delivering an incomplete habitat that is then outfitted via subsequent cargo delivery flights.

The study assumes that the Common Habitat is offloaded from its lander and this offloading serves as the point of handover to the surface transportation system. Effectively, the lander offloading system must only lower it to a level where the surface transportation system can take over.

The study also assumes fully automated surface transportation. There are no crew involved in any way in surface transportation and potentially no crew on the surface or in orbit during surface transportation operations. Mission Control support is assumed to be responsible, but no direct tele-operation by Mission Control personnel is assumed to be required.

Objectives of Paper

One of the key open questions in the Common Habitat architecture is how to deliver a habitat as large as the Common Habitat to a predetermined position within a surface infrastructure. The subset of this problem addressed in this paper is the multi-kilometer transport of this habitat from its landing site to its intended surface habitation location.

From a mass and distance perspective, this would be somewhat analogous to moving the Space Shuttle Orbiter (not the entire shuttle stack) from the Vehicle Assembly Building at Kennedy Space Center to Launch Pad 39A or B, but doing so over unprepared, off-road terrain in lunar or Martian environmental conditions. This paper will summarize and critique initial brainstormed options that may potentially meet this challenge.

2. VALUE OF SURFACE TRANSPORTATION

Landing and Habitation Zone Attributes

The Landing Zone is a predefined, dedicated region for repeated landings. It includes navigation aids as well as multiple non-overlapping landing areas, each of which is 100 meters in diameter with a slope of five degrees or less. A power terminal is connected to the surface power infrastructure and cable carts can deploy up to 200 meters of cable from this terminal to supply ground power to active landers. There will generally always be one active crew and logistics lander present. The dedicated cargo landers that initially delivered the base camp are assumed to be unable to launch and are permanently present. Additional landing areas can be created as needed within the Landing Zone. [3]

The Habitation Zone features a leveled, 60-meter diameter region with the Common Habitat at the center. An airlock, up to two logistics modules, and up to two pressurized rovers are docked to its four docking ports, with the rovers typically docked to each other. Unpressurized rovers and external robotic systems are parked in this region when not in use. A thermal radiator array and communication tower are physically separated from the habitat complex, connected via buried conduit. External lighting illuminates the region during periods of eclipse. An interferometry array of nine 1.5-meter telescopes surrounds the Habitation Zone with diameter of ~2 km. [3]

The two zones are separated to ensure that the thrust from incoming landers does not blast the Habitation Zone elements with potentially damaging ejecta. There is also some consideration that the Habitation Zone should be protected from shrapnel generated by a launch or landing mishap. While the actual needed separation distance is heavily influenced by terrain and would thus be a variable specific to the selection of both landing and habitation zones, a distance of 3.5 kilometers is used in Common Habitat architecture studies.

Benefits Enabled by of Surface Transportation

While the Common Habitat is the largest individual element it is not the only element landed on the surface. A surface transportation infrastructure enables consolidation of launch/landing operations at a maintained site. It further separates habitation from launch and landing operations, protecting habitation systems from potential exposure to ejecta and other hazards.

A surface transportation architecture also allows the habitat site to be prepared prior to habitat arrival. Because the habitat site is not the landing site, any trenching, grading, or other surface preparation activity can be conducted without concern of either making the site unsuitable for landing or of suffering significant site erosion due to contact with lander thrust plumes.

The previous noted trenching is a key site preparation activity needed to lower the habitat's docking ports to the proper level for pressurized docking with logistics modules, the airlock, and the pressurized rovers.

Clearance needed around habitat for docking and undocking logistics and Safe Haven operations

3. CORE ELEMENTS ENABLING SURFACE TRANSPORTATION OPTIONS

Lunar Gantry

A lunar gantry is a promising concept for lifting, positioning, and transporting large elements on the lunar surface. NASA has not yet performed detailed designs of this concept, but NASA has sponsored two related challenges that matured concepts on the lunar gantry. There was a public challenge managed by Hero-X for NASA to collect ideas for cargo offloading that begin in 2020 and culminated in early 2021. [10] Three of the six winners were lunar gantry concepts. And another challenge managed by GrabCAD for NASA collected notional CAD models specifically for lunar gantries and received 130 submittals, including the one shown in Figure 5. [11] Early notional designs of a lunar gantry rely on inflatable beams with wheels on one end and joint attachments on the other end to create a mounting point for a crane hook that will support a load inside the area of the gantry wheels. These lunar gantry designs are predicated on the use of materials designed for inflatable space structures which has made rapid advances in recent years through technology maturation efforts and through demonstrations such as on the International Space Station. [12]

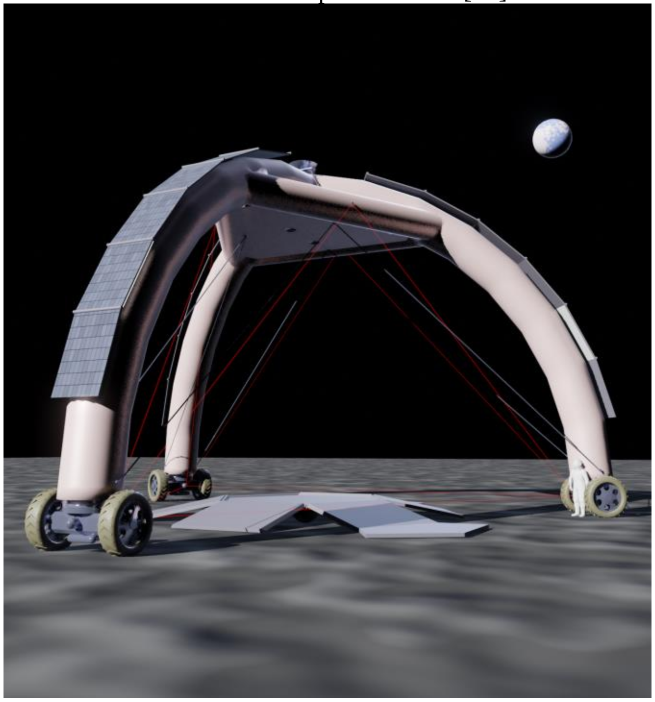

Figure 5. Lunar Gantry Concept from NASA GrabCAD Challenge. Credits: GrabCAD/Christie S

Additionally, because the inflatable lunar gantry design concept uses the same inflatable structure technology demonstrated at the International Space Station (ISS) with the Bigelow Expandable Activity Module (BEAM) module, it can be compressed in a small volume for launch and inflated on the lunar surface thus minimizing its impacts on the cargo manifest. The lunar gantry would need to position itself directly over the load's lifting point. Alternately, a pair of lunar gantries could be utilized if the habitat design encompasses lifting points at opposite ends. The existing lunar gantry concept designs were based on a projected mass of 10-15 metric tons based on payload mass requirements expected of cargo-only versions of Human Landing Systems class lander as documented in the NASA NextSTEP Appendix P Request for Proposals [13] released in September 2022. Therefore, an application of lunar gantries for masses up to 90 metric tons would have to be scaled up appropriately and/or engage the application of multiple scaled lunar gantries at opposite ends of the habitat. Depending on the specific gantry design, surface preparation may or may not be required to create a path on which it can traverse.

Chariot

The Chariot is a prototype multipurpose mobility chassis originally developed under the NASA Constellation program. [14] The Chariot can serve as a cargo platform, an unpressurized crew rover, or the mobility chassis of a pressurized rover. A first-generation prototype is shown in Figure 5.

Figure 6. First Generation Chariot Prototype Configured as an Unpressurized Rover

A small prototype variant dubbed "Centaur," shown in Figure 6, was used as the mobility platform for the humanoid robot Robonaut. Variants of the Chariot have over the years included four or six individual wheel modules, with one or two wheels per module. Its successor is the Artemis Lunar Terrain Vehicle.

Figure 7. Centaur Prototype with Robonaut

ATHLETE

The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) was developed by the Jet Propulsion Laboratory (JPL), also during the Constellation program, as a robotic system to carry heavy payloads across irregular terrain. [15] A half-scale prototype of the ATHLETE is shown carrying a prototype habitat in Figure 8. The ATHLETE can split into two three-limbed halves, as shown in Figure 9, giving it the ability to grapple payloads from the side. While JPL has continued some ATHLETE development since the cancellation of the Constellation program it is not currently used in any active NASA programs.

Figure 8. Half-Scale ATHLETE Prototype Carrying Mockup Habitat Module

Figure 9. ATHLETE Separating into its Two Halves

LSMS

The Lightweight Surface Manipulator System (LSMS) was developed by the Langley Research Center during the Constellation program to unload landers by lifting and precisely positioning equipment. [16] A prototype of the LSMS is shown during a field test in Figure 10.

Figure 10. Field Testing of LSMS Prototype

A rendered image showing how the LSMS might be used on the Moon is shown in Figure 11. Variants of the LSMS have been proposed in numerous applications since Constellation but it is not currently an active part of any NASA program. There are mobile and fixed options for the LSMS, and any specific use case would have to be tailored for the habitat mass with an appropriate tip-over analysis to assess whether additional stability implements are required such as guy wires and/or anchors.

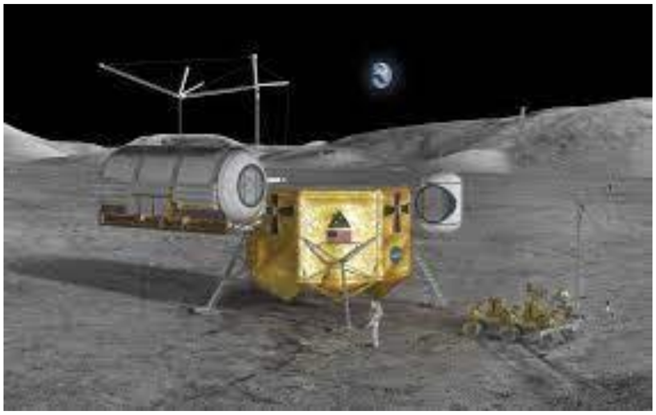

Figure 11. Illustration of Heavy LSMS Unloading a Habitat Module from a Lander

Variations and hybrid combinations of these elements were used in this study to develop notional transportation options for the Moon and Mars, given different habitat masses.

Imagery of all mobility and manipulation systems are notional artistic concepts for illustrative purposes only, in some cases incorporating borrowed pieces of CAD elements from other studies and do not constitute current or expected actual flight vehicles. There are no current NASA use cases that utilize mobility or manipulation assets in the manner discussed in this paper and there is no correlation intended between the systems described in this paper and current Artemis surface elements.

Sequence of Element Delivery to the Surface

The Common Habitat Architecture allocates the delivery of surface elements in three distinct phases. A mass / volume packaging study is planned as forward work to determine how many lander missions are contained within each phase. Phase one delivers the following surface elements:

1. Surface Transportation System (qty = 1)
2. Multi-Gravity Active-Active Mating Adapter (qty = 1)
3. ATHLETE (qty = 4)
4. Bulldozer Blade (qty = 3)
5. Regolith 3D Printer (qty = 3)
6. 3D Printing Binder Material
7. Regolith Microwave Sintering Device (qty = 3)
8. Laser Sintering Device (qty = 6)
9. Digging Bucket (qty = 3)
10. Regolith Advanced Surface Systems Operations Robot (qty = 3)
11. ~2 [TBR] MW Nuclear Power Element (qty = 1)
12. External Communications Array (qty = 1)
13. Pressurized Rover (qty = 2)
14. Unpressurized Rover (qty = 2)

Any surface preparation activities (digging, trenching, cable laying, etc.) can be conducted once the Phase one elements are on the surface. Phase two delivers the following surface elements:

1. Surface Transportation System (qty = 1)
2. Multi-Gravity Active-Active Mating Adapter (qty = 4)
3. Airlock (qty = 1)
4. Airlock support cradle (qty = 1)
5. In-Situ Resource Utilization Equipment
6. Interferometric Telescope Surface Instrument (qty = 9)
7. External Telemetered Science Instrument (qty = 3)
8. ATHLETE (qty = 4)
9. Habitation Zone Heat Rejection Assembly (qty = 1)
10. External Communications Array (qty = 1)

Phase three is devoted specifically to delivering the Common Habitat (qty = 1).

4. ENABLING INFRASTRUCTURE

The lunar surface has many challenges for transportation due to its dusty and rocky terrain. During Apollo missions, astronauts had problematic instances with lunar dust and terrain during surface operations and operating the Lunar Rover Vehicle (LRV). The transportation route of the Common Habitat from the lander to surface Habitation Zone may have many obstacles to overcome and potentially risks or damage to the transporters. It is possible that the transporter may be designed to overcome these obstacles and risks. However, another option is to reduce the risk of moving systems along a planetary surface by utilizing relatively simple roads or paths between destinations to reduce the risk with hazards and lofted regolith dust that would exist without some means of preparation. [5], [6]. Autonomous or tele-operated rovers could assist the transportation by removing boulders and smoothing over hills/craters of the transit route prior to arrival of the Common Habitat to the lunar or Mars surface.

Preparation of a transit path could first be established using a rover such as the Pressurized Rover, Chariot [7], and/or ATHLETE [8] – all of which are present in the Common Habitat Architecture – equipped with a bulldozer blade to both move boulders out of the path and level the surface along the path. Figures 12 and 13 show bulldozer blades on the Chariot and ATHLETE respectively.

Once the path is established, there will still be significant loose regolith that could impact a surface transport vehicle and the habitat as they transit along the path. To minimize undesirable impacts due to regolith that would be lofted during transport, the regolith can be stabilized along the newly established path. Stabilization solutions for route surface include preparing the surface by sintering or spraying polymers. Sintering lunar dust together would form a solid road and might better support the loads of the habitat than unprepared terrain. Spraying a polymer application would also solidify the regolith surface but the application could be more difficult on the lunar surface compared to sintering [9]. Having a clear and solid route would ensure ease of transportation of the habitat to its Habitation Zone.

Figure 12. Bulldozer Blade on Chariot Prototype

Figure 13. Conceptual Image of Bulldozer Blade on ATHLETE

Also, communications relays and/or cameras placed at optimal locations along the transportation route will assist in facilitating the transit. The communications relays and/or cameras may be used for monitoring the Common Habitat and transporters to ensure the hardware is meeting transportation check points and identify any off-nominal activities or hazards to the hardware. Alternately, mobility assets equipped with cameras and communications systems could accompany the transportation and provide the same services. Regardless, the use of an autonomous or tele-operated transportation of the Common Habitat reduces hazardous surface operations during the transit and enables habitat emplacement prior to crew arrival.

5. LUNAR SURFACE TRANSPORTATION OPTIONS

Chariot-Derived 30-Ton Lunar Transporter

This transporter is based on a notional uncrewed mobility chassis with a mass of 500 kg and a lunar payload capacity of 6000 kg, capable of traversing slopes up to 20 degrees. An estimated 4,360 kg of support truss is utilized to link the chariots and form the structural platform that carries the Common Habitat. Six chariots are utilized to achieve the needed carrying capacity, shown as such in Figure 14. It should be noted that 30 tons indicates the mass, not weight, of the payload. A payload with a mass of 30 tons of course weighs less on the Moon than on Mars or Earth and a 30-ton lunar transporter therefore cannot transport 30 tons on either Mars or Earth. (Mass does not change with gravity, but weight does.)

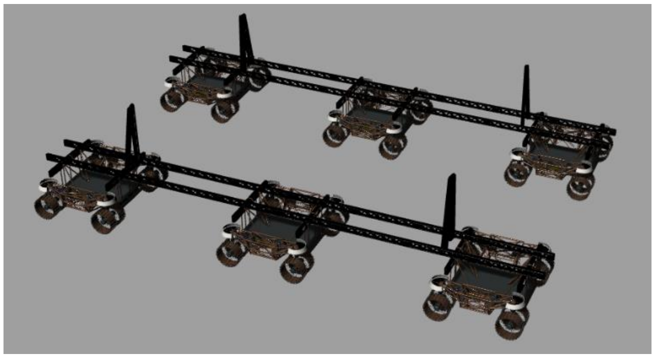

Figure 14. Chariot-Derived 30-Ton Lunar Transporter

The Common Habitat is secured to the transporter with four vertical structures, as shown in Figure 15, each attaching to the ring frames of the Common Habitat pressure vessel, at the intersection of the dome and barrel sections.

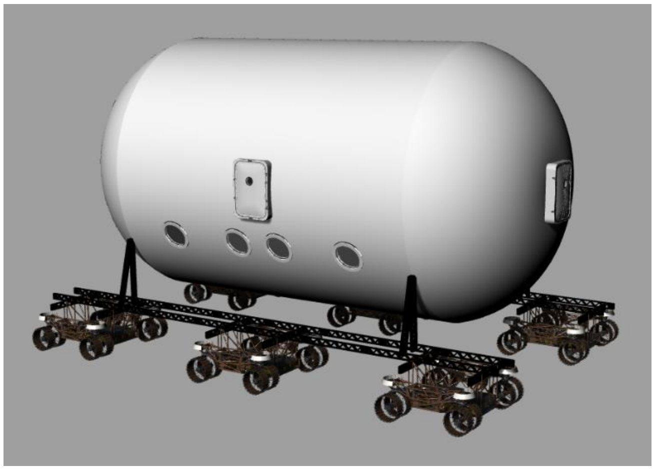

Figure 15. Common Habitat Carried by Chariot-Derived 30-Ton Lunar Tr0ansporter

The team had several impressions regarding the use of the Chariot platform to derive a 30-ton Lunar Transporter. On the positive side, it reflects a relatively simple configuration and is adaptable to other payloads of varying masses. It inherently features common, interchangeable parts, supporting sparing strategies.

On the negative side, relatively smooth terrain is required to properly align transporter-habitat interfaces due to limited vertical adjustability in the Chariots. It is possible, though, that hinged trusses between Chariots (at the cost of increased mass and complexity) might enable greater variation in terrain. Regardless, rises or falls in traversing risk causing high centering or concentrating loads on a small number of Chariots, further indicating a need for adjustability in the truss structure beyond the inherent suspension within each Chariot's wheel assemblies. Additional launches and potential extra-vehicular activity (EVA) or extra-vehicular robotic (EVR) assembly operations will be needed for the support truss. The trusses will bend, causing the load to focus on the extreme ends. (A preloading could be imposed on truss segments to counter this but would have to be tuned to a specific load.) Finally, there may be scaling issues with the wheels – it was not clear to the team if the nominal wheels (for a single Chariot) would be the correct ones for a set of Chariots used in this manner due to the concentrated loads. Ultimately, the team considered this concept worthy of further engineering study but not an ideal approach.

Chariot-Derived 50-Ton Lunar Transporter

A similar approach was employed for the 50-ton Common Habitat variant. In this case, eleven Chariots are used to form the mobility platform, with an estimated 7,260 kg of truss structure to connect the Chariots and habitat. Figure 16 shows the resulting transporter system.

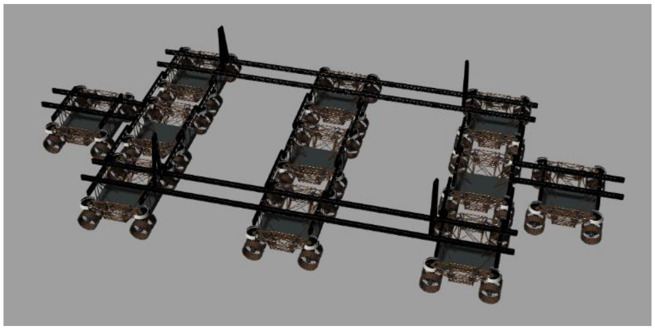

Figure 16. Chariot-Derived 50-Ton Lunar Transporter

The Common Habitat is transported on top of this platform in the same manner as the 30-ton variant, shown in Figure 17.

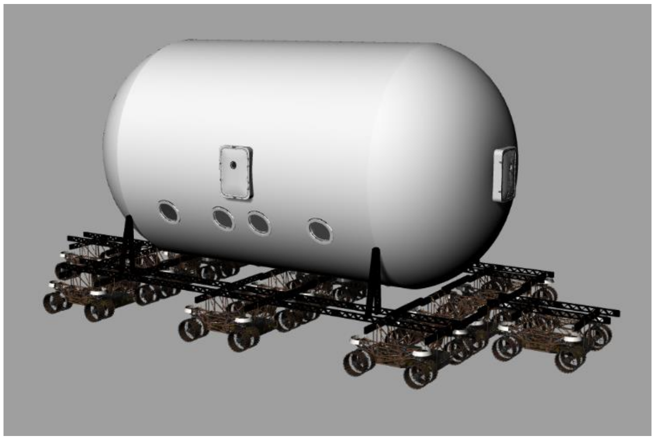

Figure 17. Common Habitat Carried by Chariot-Derived 50-Ton Lunar Transporter

Team impressions built on those established for the 30-ton transporter. With a greater payload capacity, it has adaptability to an even wider range of payload masses. The team also noted it should be viable with a range of different payload center of gravity (c.g.) configurations. The team was reminded that there is some heritage in Earth-based mobility systems.

However, it is suspected that it will be challenging to align structural interfaces since port and starboard interfaces cannot operate independently. The increased number of Chariots was significant as it is expected that these elements are not needed on the surface for any other purpose than this one-time transport. The load distribution is expected to be a complex engineering challenge to avoid loading the four corners only (and will need a custom-mass support structure).

This concept was suspected by the team to be politically non-viable in addition to its technical challenges, primarily due to the number of additional lunar landings needed to deliver the increased number of Chariot elements.

Chariot-Derived 90-Ton Lunar Transporter

The 90-ton Lunar Transporter is the first variant that can actually transport the envisioned Common Habitat, fully outfitted. However, this capability comes at a cost. The transporter, shown in Figure 18, is supported by seventeen Chariots with 8,800 kg of support truss hardware.

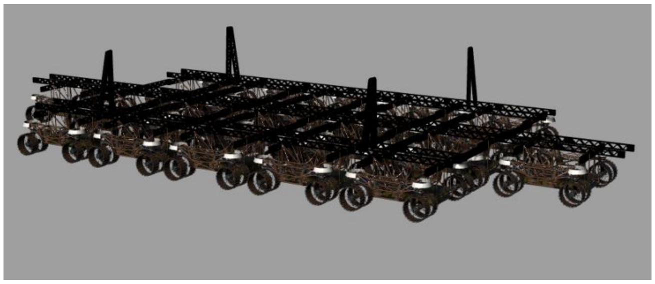

Figure 18. Chariot-Derived 90-Ton Lunar Transporter

The Common Habitat is transported on top of this platform in the same manner as the 30-ton and 50-ton variants, shown in Figure 19.

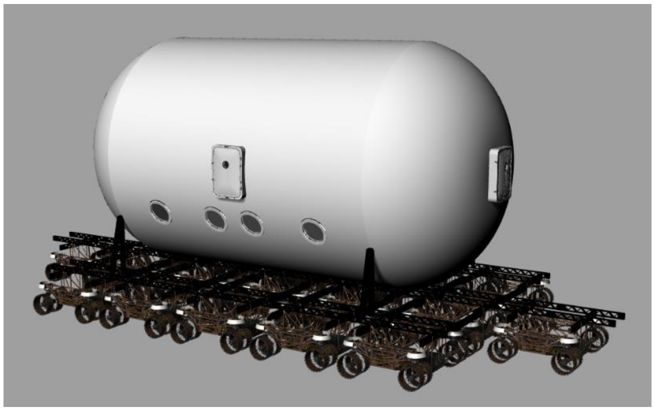

Figure 19. Common Habitat Carried by Chariot-Derived 90-Ton Lunar Transporter

The most significant benefit of this transporter is that it can transport the complete Common Habitat, with no subsequent outfitting missions needed to prepare it for the first crew use.

However, all of the prior negative attributes are repeated for this transporter. Additionally, due to the relatively spacing of Chariot elements, it is unlikely that any adjustability in the truss structure would be possible. Thus, it would be the most likely of the three variants to require a flat, prepared surface for transport between the lander and Habitation Zone.

The team concluded that this transporter concept is non-viable due to its technical and political challenges.

ATHLETE-Derived 30-Ton Lunar Transporter

JPL has an internal sizing tool used to estimate various performance features of the ATHLETE as a function of size and gravity environment. Based on this tool, a 7,901 kg ATHLETE can lift and carry 15,000 kg on the Moon and can traverse greater than 20-degree slopes. Two of these ATHLETES can split into their halves, such that the four three-limbed robots can directly mate to the Common Habitat's ring frames with no additional support truss needed, as illustrated in Figure 20.

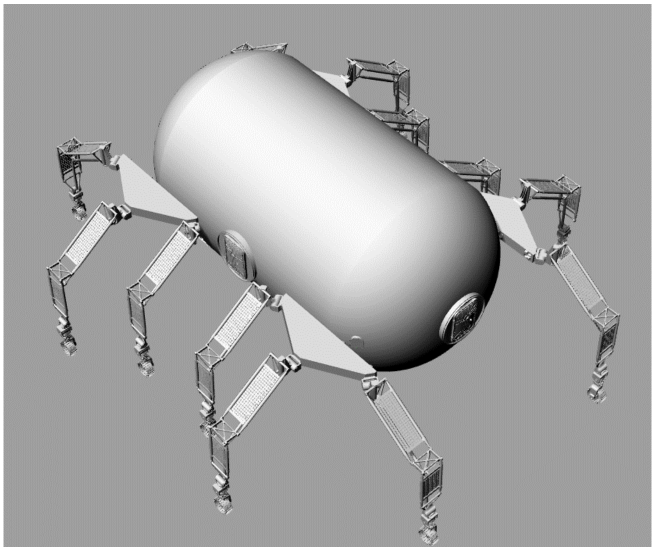

Figure 20. Common Habitat Carried by ATHLETE-Derived 30-Ton Lunar Transporter

The team felt that this transporter was beneficial in that it showed high potential reuse of all ATHLETE elements in other surface operations. The greater stroke of ATHLETE over Chariot meant that it can more easily maintain balance of load and number of contact points needed while maneuvering. The only negative is because it can only lift a 30-ton Common Habitat, more outfitting flights are needed to achieve the habitat's 90-ton control mass. The team felt that this is a viable surface transportation system.

ATHLETE-Derived 50-Ton Lunar Transporter

For the 50-ton Common Habitat case, the transporter uses four complete ATHLETEs along with an estimated 1,235 kg of support truss needed to connect the habitat to the ATHLETEs. The configuration, shown in Figure 21, is similar to the 30-ton case, but an entire ATHLETE is located at each corner.

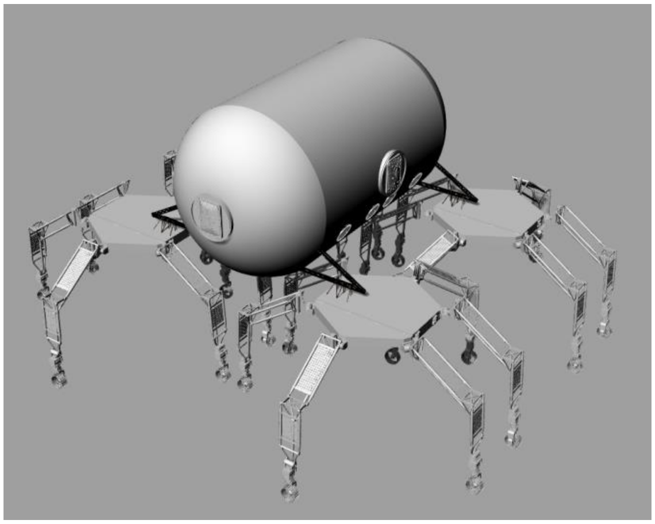

Figure 21. Common Habitat Carried by ATHLETE-Derived 30-Ton Lunar Transporter

Because the four ATHLETE transporter has additional margin (60-ton capacity vs. 50-ton load), the team felt that it has greater resilience to system failures and better access for maintenance. However, doubling the number of limbs also means more complex communication between modules. This was also deemed a viable surface transportation system.

ATHLETE-Derived 90-Ton Lunar Transporter

The 90-ton Common Habitat drove the selection of a different ATHLETE with the JPL sizing tool. The 4,891 kg ATHLETE offered a lighter total mass and superior margin over the 7,901 kg ATHLETE for this payload mass, with each ATHLETE able to carry 11,455 kg on the Moon. A total of eight of these ATHLETEs are needed. (While six of the heavier ATHLETEs can lift exactly 90 tons, the six ATHLETEs have a combined mass of 47,406 kg versus 39,128 kg for the eight lighter ATHLETEs, which can lift 91.64 tons.)

Eight ATHLETES did pose a challenge for transporting the Common Habitat – there is insufficient room surrounding the habitat for eight ATHLETES to gather around it. In order to achieve this, a modified version of the ATHLETE is considered where its “deck” is reconfigured as a rectangular structure and the eight ATHLETEs are linked into two large structures, each lifted by twenty-four limbs – each effectively combines four ATHLETEs into one heavy lift robot. These two robotic systems directly attach to the Common Habitat, one on each side as indicated in Figure 22.

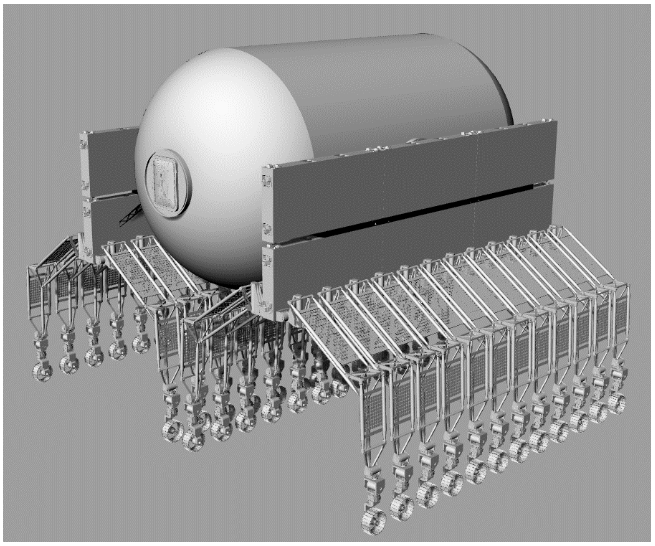

Figure 22. Common Habitat Carried by ATHLETE-Derived 90-Ton Lunar Transporter

The primary advantage of this system is that it is able to transport the fully outfitted Common Habitat. However, additional engineering would be required to repackage ATHLETE systems and it is not entirely clear how it transforms between its nominal single-ATHLETE configuration and these merged ATHLETE transporters. Despite these challenges it was deemed a viable surface transportation system.

LSMS-Derived System

A crane is generally considered to be a lifting device as opposed to a transportation system. But a 90-ton LSMS-derived surface transportation system will be discussed in the Mars surface transportation options.

6. MARS SURFACE TRANSPORTATION OPTIONS

Chariot-Derived 30-Ton Mars Transporter

This Chariot-derived transporter used a similar approach to its lunar counterparts, but the increased gravity of Mars meant a greater number of Chariots would be needed to lift the same mass. It was also assumed that the Martian gravity would result in design changes to the Chariot itself, with a Mars Chariot having an estimated mass of 1088 kg and a payload capacity of 2200 kg, still capable of traversing up to 20-degree slopes.

Based on this Chariot variant, a Mars Transporter consisting of nineteen Chariots with 9,420 kg in support trusses, shown in Figure 22, was estimated to carry a 30-ton Common Habitat. As previously noted, a 30-ton payload weighs more on Mars than the Moon, requiring not only a larger Chariot but also a greater number of Chariots than are required to transport a mass of 30 tons on the Moon.

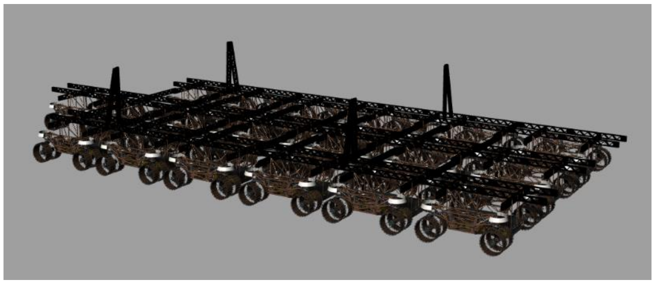

Figure 23. Chariot-Derived 30-Ton Mars Transporter

The same four-point attachment structure was used to transport the Common Habitat on top of this platform as seen in Figure 24.

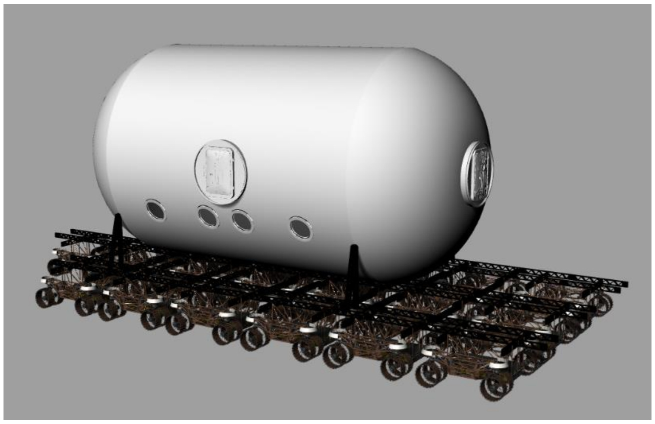

Figure 24. Common Habitat Carried by Chariot-Derived 30-Ton Mars Transporter

The Mars Transporter inspired the same positive impressions as its Lunar variants. However, if seventeen Chariots was considered a non-viable solution for the Moon, nineteen Chariots is clearly worse as a solution for the more distant Mars. While the following is also true for the Moon, it was not until the Mars study that the team also noted that variations in terrain may cause loss of traction – how many wheels are required to push/pull the hab vs. carry the load of the hab? Additionally, maintenance of the inner Chariots may be challenging if the system cannot disassemble for servicing.

The number of delivery flights (and associated Earth launches) needed to deliver this system to Mars caused the team to consider it non-viable. As a heavier Common Habitat would require even more Chariots, this is the only Chariot-derived system considered for Mars.

ATHLETE-Derived 30-Ton Mars Transporter

The Mars 30-ton Common Habitat case used the 4,891 kg ATHLETE variant, which can lift 5,000 kg on Mars. This approaches the upper limit of ATHLETE's reasonable capacity where the mass of the ATHLETE has grown to nearly equal the mass of the payload itself. While larger ATHLETEs are possible, their benefits begin to be outweighed by their mass. Six of these ATHLETEs are needed to lift the Common Habitat, arranged in a similar configuration to the 90-ton Lunar case and illustrated in Figure 25.

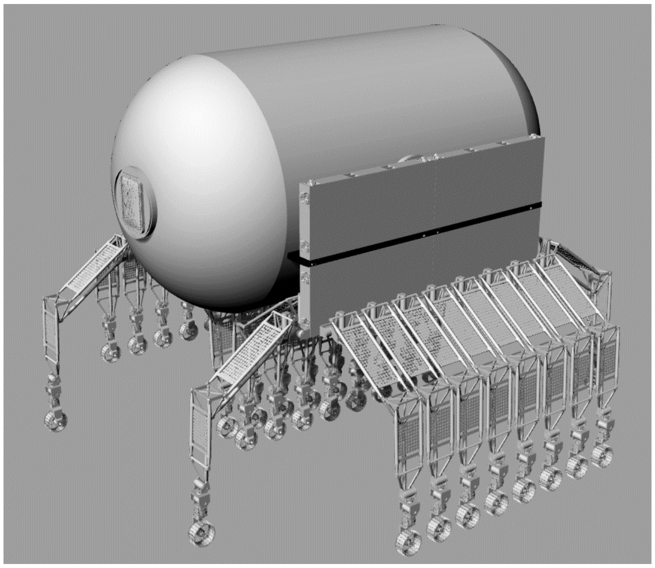

Figure 25. Common Habitat Carried by ATHLETE-Derived 30-Ton Mars Transporter

This variant surface transporter was deemed useful in that all of the ATHLETE elements do have other uses on the surface after habitat transportation, thus no elements are needed exclusively for transportation of the habitat. However, it shares with the 90-ton Lunar Transporter the need for additional engineering development to enable this reconfiguration of the ATHLETE. And it requires additional outfitting flights to deliver the 60 tons of internal systems removed for the habitat to meet this mass target. This surface transportation element was deemed viable.

Hybrid Chariot and ATHLETE Derived 90-Ton Mars Transporter-Crawler

Both the Chariot and ATHLETE-derived Mars transporters maxed out in the 30-ton capacity range. A surface transportation system capable of transporting a 90-ton Common Habitat requires either 24 ATHLETEs or 44 Chariots. It is challenging (though not necessarily impossible) to cluster this many mobility systems around the habitat. However, the hybrid system represented in Figure 26 was considered as a means to package a mobility system more effectively, with equivalent payload capacity.

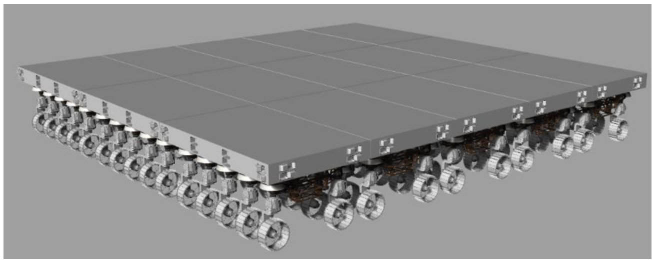

Figure 26. Hybrid Chariot-ATHLETE-Derived 90-Ton Mars Crawler-Transporter

This system is a platform consisting of fifteen structurally connected modules, each of which features ATHLETE wheel modules held by Chariot suspensions. A truss structure holds the Common Habitat on the crawler-transporter, as seen in Figure 27.

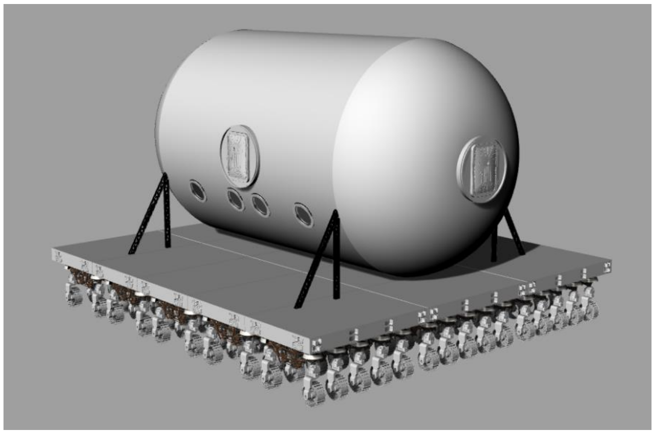

Figure 27. Common Habitat Carried by Hybrid Chariot-ATHLETE-Derived 90-Ton Mars Crawler-Transporter

The crawler-transporter has the clear benefit that it transports the entire 90-ton Common Habitat without any need to offload its outfitting to subsequent flights. It is easily adaptable to payloads of varying masses, even to the extent of separating into its constituent modules, each of which can carry up to 6,000 kg. The stroke in the suspension enables it to operate within a wide range of c.g. configurations. However, it is likely not viable on unprepared surfaces for the same reasons as the Chariot-derived transporters. Surface preparation would be necessary for the entire route between the lander and Habitation Zone. More concerning, it is possible that the first several rows of wheels will disturb an untreated surface sufficiently that the terrain may be untrafficable by the time the rear wheels reach it. Thus, surface preparation may involve more than just leveling. It may require actual paving with sufficient load-bearing capability to not be damaged by the mass of the combined crawler-transporter and habitat. This system was deemed viable only with adequate surface preparation (and the associated penalties to the architecture in terms of additional delivery flights).

LSMS-Derived Moon and Mars 90-Ton Transporter

Assuming the LSMS can be scaled up into a much larger system, one or two LSMS devices, each capable of lifting 90-100 tons, can be used as part of a system to transport the Common Habitat. The LSMS, which is assumed to have a mass of 10,000 kg or less, is transported by one or two ATHLETEs. It is positioned next to the Common Habitat. It then lifts the habitat, pivots the habitat 180 degrees (± any intended course changes), and sets the habitat down. The LSMS is then repositioned by the ATHLETE(s) to the opposite side of the habitat. The LSMS repeats the lift-pivot-set down & relocate until it has traversed the distance from the lander to the Habitation Zone (estimated ~350-400 repeats). This process is illustrated in Figure 28.

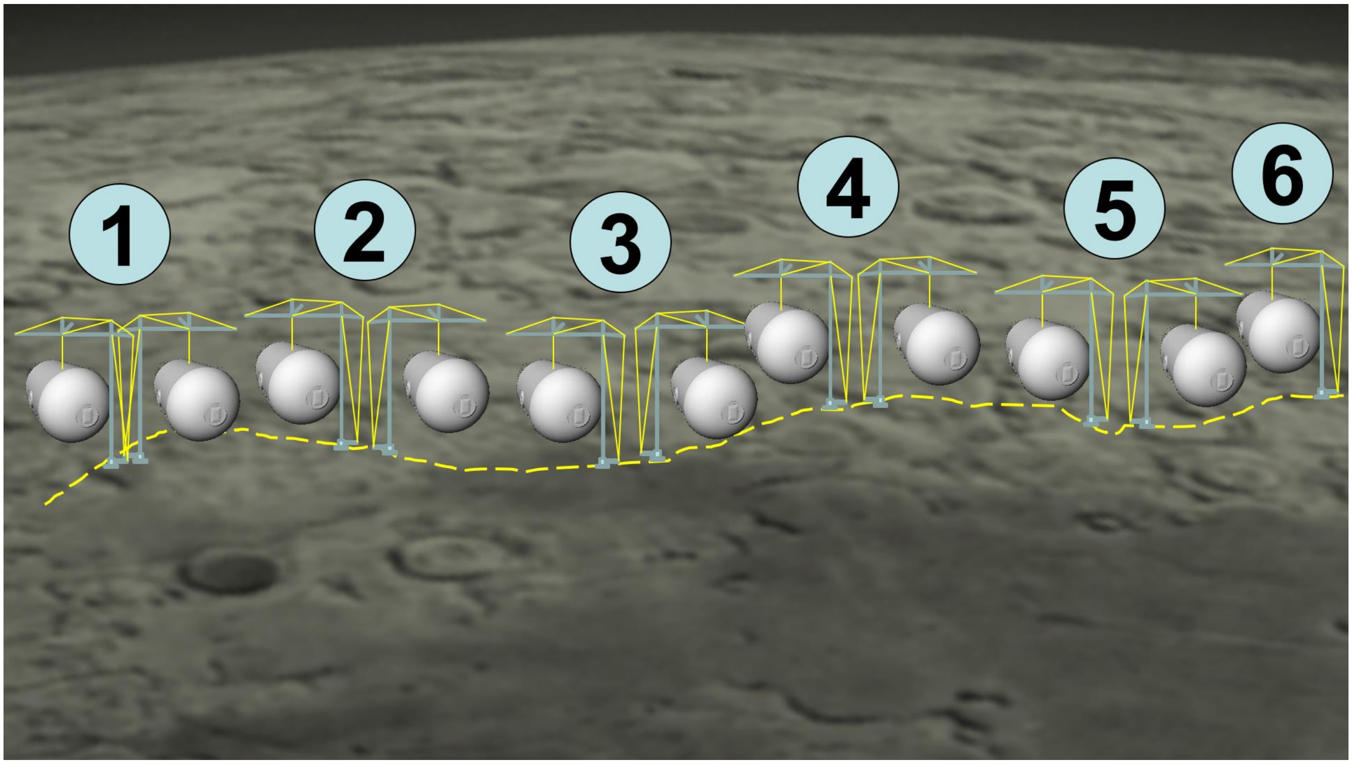

Figure 28. Common Habitat Transported by LSMS-Derived Moon and Mars 90-Ton Transporter

Step 1 indicates the LSMS first lifting the Common Habitat and then rotating it 180 degrees. Step 2 is the second lift and rotate. Step 3 the third, and so on. Effectively the LSMS transports the habitat the distance equal to its rotation and the ATHLETE repositions the LSMS to repeat the process over and over until it has reached the Habitation Zone.

The key benefit of this concept is that it does enable transport of a fully outfitted Common Habitat on both the Moon and Mars. Like several of the other concepts, this approach is adaptable to other payloads of various masses. The team recognized that an undesirable aspect is that this is a very long process due to the hundreds of crane operations required. Additionally, surface stability would need to be known for every crane operating location. The LSMS would also need to be capable of stabilizing itself across the potential diversity of terrain features it would encounter.

The team did note benefits of using multiple LSMS devices instead of just one. If a single unit is used, the Common Habitat must be lowered all the way to the surface each time, requiring additional support structure in the form of legs or a cradle of some kind. But if at least two units are used, a handover can be accomplished where the habitat is never lowered all the way to the surface but is instead transferred from LSMS to LSMS. Additional LSMS units also would provide a level of redundancy and/or reduce the number of cycles needed to be performed by each unit. Operations with multiple units will also be faster because one crane can be repositioned while the other is in operation.

This transportation system was considered viable by the team.

Similarly, a lunar gantry is a promising concept that seems viable but requires further design maturity tailored to the mass of the common habitat to develop a fully formed concept of operations for transporting the element. Assessing whether one or two lunar gantries would be required depends on the lift points on the habitat element and the capacity of each gantry. And further analysis of the lunar gantry concept may prove fruitful to the challenge of offloading the element from the lander prior to or as part of the transportation function.

7. ADDITIONAL CONCEPTS NOT ASSESSED

The team discussed several additional concepts that were generated in a rapid brainstorm session.

One idea was to place larger wheels on the habitat exterior (wheel diameter > habitat diameter). The this would enable the entire habitat to be rolled about its axis; possibly using repositionable ground anchors and winches. The team had some concern that the process would induce vibrations to the habitat interiors, and it would be unlikely to be able to certify the habitat for rolling 3.5 kilometers to the Habitation Zone. It would also be difficult to turn the structure. This concept was considered non-viable.

A second idea was to use ground anchors and winches, or a tracked mover of some kind, to pull a Common Habitat mounted on some form of skis or skid plate(s). The team noted that the tracked mover would inherently be a very large mobility system. Surface assembly would be required for the system. And either approach would require units on both ends to enable braking. This concept was one of the favored of the rapid brainstorm group.

A third idea was to redesign the ATHLETE with significantly stronger limbs to reduce the number of ATHLETEs needed for a given cargo mass. There was insufficient data to describe the implications of such an idea, but it was brought out that if optimized for the Common Habitat load, the resulting ATHLETEs might be oversized for other applications. Nevertheless, the concept was considered viable.

A fourth idea was to mount the ATHLETE limbs (in the scenarios using six or eight ATHLETEs) directly to the side of the Common Habitat. This was considered beneficial in that it enabled a load path to the individual limbs. However, it likely would require structural changes to the Common Habitat to accept loads along the length of its barrel section and it would require a redesign of the ATHELTE to package all of its systems in its limbs. The changes imposed on the Common Habitat negate many of the advantages of using the SLS production line for its manufacture and therefore render the concept non-viable.

8. POTENTIALLY VIABLE CONCEPTS

In summary, seven options were considered potentially viable for the Moon and five for Mars. The Lunar systems are:

1. Chariot-Derived 30-Ton Lunar Transporter (six Chariots)
2. ATHLETE-Derived 30-Ton Lunar Transporter (two ATHLETEs)
3. ATHLETE-Derived 50-Ton Lunar Transporter (four ATHLETEs)
4. ATHLETE-Derived 90-Ton Lunar Transporter (eight ATHLETEs)
5. LSMS-Derived, Lunar and Mars Transportation
6. Skis / Skid Plate in conjunction with tracked movers or winched anchors
7. Stronger ATHLETE limbs

The potentially viable Mars systems are:

1. ATHLETE-Derived 30-Ton Mars Transporter (six ATHLETEs)
2. Hybrid Chariot-ATHLETE-Derived 90-Ton Mars Crawler-Transporter (requires precursor transit path preparation)
3. LSMS-Derived Moon and Mars 90-Ton Transporter
4. Skis / Skid Plate in conjunction with tracked movers or winched anchors

5. Stronger ATHLETE limbs

In addition, the two crowdsourcing challenges both suggested inflatable gantry systems for payload transport and it is reasonable to assume that an inflatable gantry could be scaled up to a size capable of transporting the Common Habitat, almost certainly for the Moon and potentially even for Mars. Thus, it is also a viable option.

The Common Habitat architecture maintains commonality to the greatest extent possible between Moon and Mars systems as a means to reduce developmental timelines and expenses. Consequently, it is desired that the same system be used on both the Moon and Mars. Additionally, outfitting flights are not desired as they add significant numbers of launches to the manifest.

While surface transportation of the common habitat will be simplified by surface preparation activities such as removing obstacles, leveling surfaces, sintering, or application of sprayed polymers, any such preparation will require additional time and cost and might interfere with other site preparation activities that need to be completed before the Common Habitat is landed on the surface.in phase three of surface element delivery. Thus, the value of surface preparation trades against the capabilities of the surface transportation system.

The system that appears to be most viable while also capable of transporting a fully outfitted Common Habitat on both the Moon and Mars, while potentially requiring no surface preparation, is the LSMS-Derived Moon and Mars 90-Ton Transporter. The inflatable gantry also bears consideration, and it could well be that a fielded solution might merge aspects of an inflatable gantry with an LSMS crane system.

For the lunar base camp [3] only, a dissimilar backup system can be used for surface transportation of the Common Habitat. The base camp utilizes eight ATHLETEs for a variety of surface utility and transportation functions. These ATHLETEs could be modified to serve as a backup 90-Ton Lunar Transporter. Thus, if there is a problem with the LSMS and/or gantry system they could take over and complete the transport of the habitat. The LSMS and/or gantry system would have to be reliable by the time the Mars system is deployed, however, as there would be no backup system there.

9. CONCLUSIONS AND FORWARD WORK

The LSMS-Derived Moon and Mars 90-Ton Transporter is the only viable surface transportation system that emerged from this study to transport the Common Habitat between its landing site and the Habitation Zone on both the Moon and Mars. However, several key areas of forward work remain to define the system.

The Langley LSMS team intended from the beginning for the LSMS to be a scalable system, but they never considered 90-ton payloads. Initial studies focused on cargos up to 6 tons and a heavy lift study considered a target of 12 tons. [16] As previously noted, the gantry studies were in a similar mass range. Significant engineering work is needed to define the system. Tip over concerns will need to be addressed and may require a more involved system of ground anchors, guy wires, and/or outriggers than considered [16] by the LSMS or gantry teams.

It will also need to be determined how the LSMS and ATHLETE receive power. Both could use onboard batteries, potentially recharged via solar arrays carried by the ATHLETE. Battery mass may be mounted in such a manner as to aid in system stability. There may also be opportunities to tap into a surface power infrastructure, either for recharging or potentially for direct power, analogous to the overhead lines or third rail used by electric trains.

Additional work is needed to define the interfaces between the ATHLETE and LSMS. The ATHLETE may only serve to transport the LSMS, but it could potentially also provide some or all of the structural ground interface, power, video imaging, data, processing, and/or communications.

System simulations of the resulting concept will be needed to refine the design and ensure system viability with respect to structures, mechanisms, energy balance, and timelines.

Given that surface transportation of the Common Habitat is an uncrewed activity, additional study and analysis is needed to develop an uncrewed operations strategy. This will include a role allocation between onboard autonomy and Mission Control, development of appropriate end effector designs, determination of necessary sensors, and development of a sufficient communication infrastructure.

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