A Joinable Undercarriage to Maximize Payload (JUMP) Lunar Lander for Cargo Delivery to the Lunar Surface

Robert L. Howard, Jr.[1]

NASA Johnson Space Center, Houston, Texas, 77058

Currently, NASA has engaged industry to develop a series of small to medium capacity landers with payload capacities of up to 5-9 tons by the mid to late 2020s. This contrasts with the former Constellation program, where the Altair lunar lander was targeting a payload capability of roughly 14-20 tons. Investment in smaller landers may present future challenges in delivering habitat modules larger than lunar lander cabins or small logistics modules to the lunar surface. Additionally, given a projected SLS flight rate of 1-2 launches per year, a lunar surface buildup from small elements seems problematic at best. While commercial launchers provide a supplement to SLS, many of the current and projected launch vehicles deliver less than 20 tons to a Trans-Lunar Injection – even fewer to the lunar surface. However, a possible solution could emerge if the lander itself could be launched in pieces with a buildup in Cislunar space. Thus, launchers with these capacities could contribute to a lunar lander capable of delivering 30 tons or more to the lunar surface. This paper introduces the notional concept of a Joinable Undercarriage to Maximized Payload (JUMP) lander. Key elements of a proposed JUMP lander concept will be discussed, followed by recommendations and forward work.

I. Nomenclature

ATHLETE	=	All-Terrain Hex-Legged Extra-Terrestrial Explorer
BFR	=	Big Falcon Rocket
CH4	=	Methane
CLPS	=	Commercial Lunar Payload Services
CLV	=	Commercial Launch Vehicle
EUS	=	Exploration Upper Stage
GOX	=	Gaseous Oxygen
HIAD	=	Hypersonic Inflatable Aerodynamic Decelerator
ISRU	=	In-Situ Resource Utilization
IVA	=	IntraVehicular Activity
JUMP	=	Joinable Undercarriage to Maximize Payload
LH2	=	Liquid Hydrogen
LOX	=	Liquid Oxygen
LSS	=	Lunar Surface Scenario
MEL	=	Master Equipment List
Mid L/D	=	Mid Lift over Drag
MIG	=	Mars Integration Group
MMH	=	Monomethylhydrazine
MPS	=	Main Propulsion System
N2O4	=	Nitrogen Tetroxide
NRHO	=	Near Rectilinear Halo Orbit
PAF	=	Payload Attach Fitting
PEM	=	Proton Exchange Membrane
RCS	=	Reaction Control System
SLS	=	Space Launch System
SPD	=	Space Policy Directive
SPR	=	Small Pressurized Rover
TLI	=	Trans-Lunar Injection
TRL	=	Technology Readiness Level
USOS	=	United States Operational Segment

[1] AIAA Senior Member, Habitability Design Center Manager, Habitability and Human Factors Branch, 2101 NASA Parkway, Mail Code SF3

II. Introduction

When Space Policy Directive 1 (SPD-1) was released, it signaled clear direction for NASA to resume a focus on human lunar activity that was previously suspended by the cancellation of the Constellation program:

"Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations." – SPD-1.

The phrase "Long-term exploration and utilization" of the Moon strongly suggests a surface infrastructure. This implies sufficient infrastructure to support long-duration human habitation, intra-vehicular activity (IVA) focused on research and other operational mission activities, and contingency response. It also suggests a mobility system capable of supporting crew activity beyond the long-duration habitation capability. Further, it suggests an infrastructure to develop and utilize local resources. However, most NASA lunar lander focus initiated since the release of SPD-1 has focused on payload capacities only approaching the 5-9 ton level by the mid to late 2020s [1]. This is more in line with smaller vehicles such crew launch and landing capsules, small pressurized rovers (SPRs), limited capacity logistics modules, and other small surface elements not intended for long duration human habitation.

III. Challenges for Fulfillment of SPD-1

Several challenges are evident in the presumed intent of SPD-1. Significant volume and mass is required to enable the previously mentioned habitation, research, and contingency capabilities. Most surface long duration habitation studies, including studies dating before the Constellation program, have recognized a need for anywhere from 200-600 m^3 total pressurized volume. There have been outliers on both ends of the spectrum, but smaller volumes than 200 m^3 tend to make severe compromises in habitation, crew work-related functionality, or safety and maintenance capabilities.

Both modular and monolithic approaches have been considered to reach the target volume. However, the smaller the modular element, the greater the number of landers required. During the Constellation program, Lunar Surface Scenario (LSS) 8 attempted to develop a long duration outpost capability using solely the pressure shells of Small Pressurized Rovers (SPRs), as shown in figures 1 and 2. Ultimately, adapting the identified capabilities into those small volumes required 25 docked SPRs to accommodate all needed crew functions, stowage, and outpost subsystems. This was a nonstarter for many reasons.

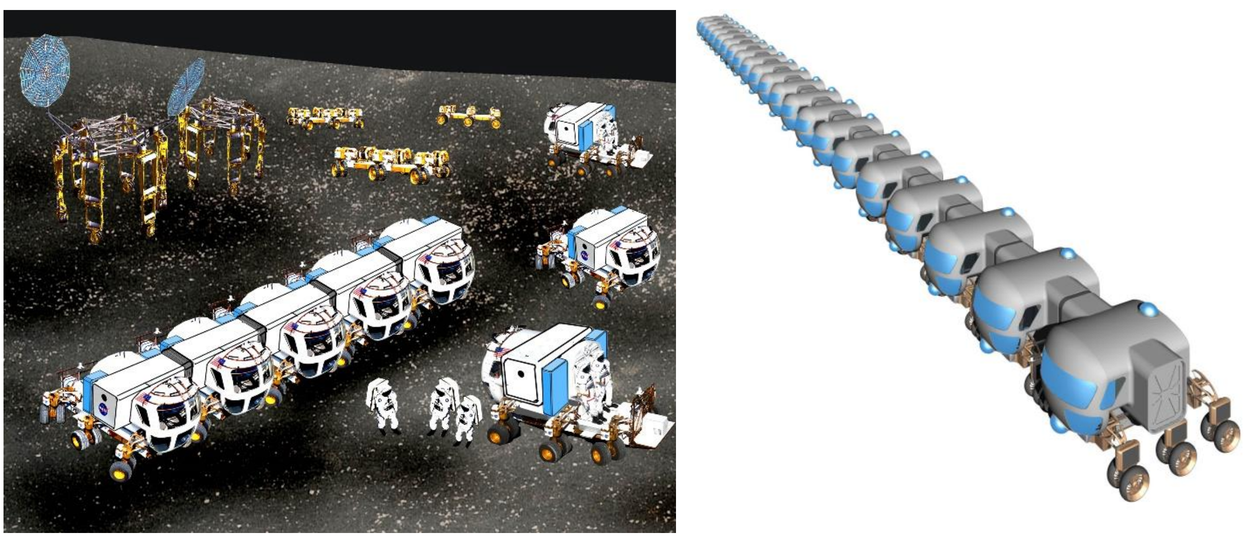

Fig. 1 Partial Assembly of LSS Scenario 8 Outpost

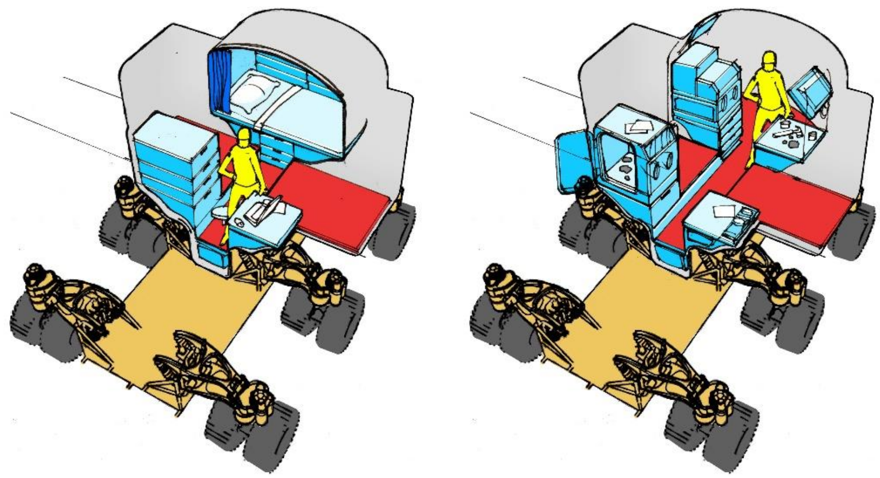

Fig. 2 Two Examples of SPR Elements for the LSS Scenario 8 Outpost – Private Crew Quarters and Geology Lab

A four-bay Cygnus module is potentially the largest pre-integrated habitable element that could be delivered on a 5-9 mt cargo lander. This variant of the Cygnus has a pressurized volume of approximately $40m^3$. Thus, it would require five to fifteen lander missions (each delivering a four-bay Cygnus module) to reach the traditional volume ranges of 200-600 m^3 total pressurized volume expected for long duration habitation.

For the International Space Station, the US operational segment (USOS) includes eight pressurized modules with a pressurized volume of roughly 600 m^3. (Including the Russian operational segment the volume exceeds 1000 m^3.) While the modular approach can break the habitation down into lower mass units, both the volume and mass efficiency decreases as the number of modules increases. If flight manifesting opportunities further constrain the total number of module deliveries, reductions in the performance or capacity of each internal function may need to be reduced as a result.

By comparison, if the pressurized volume is delivered in one monolithic element a large size is required. Recent Skylab II habitat studies (long duration habitat based on using a converted SLS propellant tank, much as the original Skylab used a converted Saturn V propellant tank) range from a 7.2 to 10 meter diameter element, with many of these studies settling on an 8.4 meter diameter. The fully outfitted mass of such a habitat may exceed 50 tons. A recent NASA Mars transit habitat study had a control mass goal of 45 metric tons, but team estimates ranged from roughly 40-60 tons. Given that surface habitats have a slightly wider range of functions than transit habitats (for instance they must also support maintenance and repair of the associated SPRs and surface EVA suits), there is no reason to believe long duration surface habitats can be any lighter than transit habitats. It is true that some mass can be offloaded to logistics (an empty habitat can be landed with certain subsystems or supplies delivered on later flights) but each new logistics flight is a new lander flight, with associated Earth launch vehicle and program cost impacts. In virtually all cases long duration surface habitation requires either many lander flights or a smaller number of very large capacity (both payload mass and payload volume) lander flights. If not, habitat capability must be reduced to levels that impact mission performance and potentially crew safety.

Further complicating the challenge for fulfilling SPD-1, the availability of NASA's new super-booster, the Space Launch System (SLS) is not as great as many surface architects would prefer. Kennedy Space Center is unlikely to be able to launch more than two SLS missions per year unless additional investment is made to expand launch processing facilities. However, the Gateway and lunar programs will require at least one SLS flight per year for crew launches. Initially, these missions were co-manifested flights where SLS was to deliver both the Orion capsule and a Gateway payload, with the second payload limited to the 8-10 ton range. However, recent Administration proposals look to potentially eliminate the SLS Exploration Upper Stage (EUS) [2] and without the EUS those secondary payloads cannot fly on SLS. The total payload capacity of SLS is also significantly reduced without the EUS. This severely restricts the opportunity to fly cargo SLS missions for the purpose of deploying lunar landers or lunar payloads.

Turning to existing cargo vehicles, the Falcon Heavy is the next most capable booster after SLS. (For now this analysis ignores the Big Falcon Rocket (BFR), also known as "Super Heavy", as that vehicle is not yet operational. Its existence will provide additional options once available.) The Falcon Heavy's payload delivery capacity to Cislunar space is less than the cargo-only SLS, but more than the co-manifested slot available on SLS when payloads must be delivered along with Orion. Also, the Falcon Heavy payload fairing is not as large as the SLS fairing, making the Falcon Heavy both diameter limited and mass limited. Other new boosters such as the New Glenn and Vulcan offer promises of comparable performance to Falcon Heavy, but for this analysis the focus will be on the Falcon Heavy as it is currently operational. Smaller CLVs (e.g. Delta IV Heavy, Atlas V, etc.) have less payload capability and are not viable options.

The challenge at this point is to use CLVs to land a 30-60 ton payload on the lunar surface, with the constraint that each CLV can deliver a payload no greater than 16.8 tons to a trajectory to Cislunar space. A surface hab target mass of 45 tons is based on the Mars transit hab, with 60 tons as an absolute upper limit and 30 tons as a lower limit to assume significant offloading that may be contained in one or at most two logistics flights.

IV. Key Assumptions

This analysis is guided by a number of key assumptions:

1. Only available CLV to deliver lander is Falcon Heavy (or comparable performance commercial rockets)
2. Launch vehicle payload performance to TLI is ~16.8 mt
3. Multiple CLV launch sites and multiple launch ranges (or rapid site/range turnaround) available
4. CLVs can launch within seconds to days of each other
5. Lunar lander payload may be either a crewed Ascent Module or cargo element(s)
6. For crew missions, Ascent Module is mated to top of the lunar lander
7. For cargo missions, cargo is mated to top of lunar lander
8. Mating of Ascent Module or cargo to lunar lander is accomplished in space
9. Ascent Module is reusable and is maintained at Gateway when not in use
10. Lunar lander is (eventually) reusable
11. Lunar landers are stockpiled on surface until reuse is possible
12. Payload is launched separately from lunar lander

V. JUMP Lander Concept

With these assumptions in place, lander concept can emerge that operates within the CLV mass and volume constraints but delivers the target payload mass and volume to the lunar surface. This research proposes a Joinable Undercarriage to Maximize Payload (JUMP) lander. The JUMP lander consists of three identical core stages that are launched separately and are assembled in space. For this initial study, the JUMP lander core stages are constrained to a launch mass of under 16.8 tons, ensuring they can be launched by the Falcon Heavy or equivalent CLV.

A. JUMP Lander Subsystems and Features

At this initial point in the JUMP lander's design, many of its key subsystems and features must be defined through a series of trade studies for future analysis. The major trades have been identified as a starting point.

The main propulsion system (MPS) will trade four types of engines: the shuttle OMS engine, the RL-10, the conceptual LOX-Methane engine used by the Mars HIAD lander concept, and the LOX-Methane Morpheus engine. The starting point for initial design studies is the RL-10 engine. In particular, a single RL-10B-2 MPS engine is initially selected for each core stage, located at the base of the core stage, mounted to the lower dome of the liquid hydrogen tank. Trade studies for the other engines may suggest different quantities and placement of engines.

The JUMP reaction control system (RCS) will trade the hypergolic R-4D thruster against LOX/LH2 and LOX/CH4 thrusters, in the case of the latter two likely utilizing laser ignition to increase thruster simplicity and reliability. Recent research suggests laser ignition can be performed directly in the combustion chamber with no premixing of the propellants needed. [3] The starting point for initial design studies is a LOX/LH2 thruster. (All trades will maintain common propellants for MPS and RCS, such that a LOX Methane MPS is matched with a LOX Methane RCS.)

The JUMP propellant tanks are driven by the MPS and RCS selections. The possible options include hypergolic monomethyl hydrazine, nitrogen tetroxide, liquid oxygen, liquid methane, and liquid hydrogen. Boiloff options for the cryogenic tanks include nominal boiloff, advanced insulation, external sun shades, and cryocoolers. Pressurization options include helium, nitrogen, and self-pressurization. The starting point for initial design is liquid oxygen and liquid hydrogen tanks with cryocoolers and self-pressurization.

The initial selection of liquid hydrogen as the propellant fuel does drive a larger liquid hydrogen tank than methane, but offers higher performance and the potential for lunar surface refueling, as will be discussed later in this paper.

In order to launch on a CLV, the tanks are constrained to fit within the Falcon 9 payload fairing's dynamic envelope, which has a diameter of 4.6 meters and a cylindrical height of 6.6 meters, with some conical volume available above the cylindrical section [4]. This available volume fits within the performance-based needs of the JUMP lander. In order to remain within a 16.8 ton mass limit, the JUMP liquid oxygen tank is estimated as a squat cylinder with a radius of 2.1 meters, barrel length of 0.38 meters, and a dome height of 0.315 meters, resulting in a volume of 11.08 m^3. The tank holds 12,646 kg liquid oxygen. The JUMP liquid hydrogen tank shares the same radius and dome height, but has a barrel length of 1.78 meters, yielding a volume of 30.48 m^3. It holds 2,150 kg liquid hydrogen.

The propellant tanks serve as the primary structure for the lander, with the LOX tank mounted directly above the LH2 tank. Structural options to connect the two tanks include conformal tanks, a truss, and an intertank. An intertank, analogous to the SLS and shuttle External Tank intertanks is the starting point for initial design structures, serving as the primary structure joining the two propellant tanks. RCS thrusters will be configured in pods mounted directly to the intertank and to the propellant tanks. Vehicle subsystems are also mounted to the inertank interior, leveraging the volume between the two tanks.

The JUMP power system is a combination of body mounted solar arrays and a proton exchange membrane (PEM) fuel cell stack. The solar arrays surround the upper portion of the propellant tanks. The fuel cell uses gaseous oxygen (GOX) and hydrogen bled off from the propellant tanks. Water is retained in a tank for removal and reuse on the lunar surface. Other possible power system trades include methane-based fuel cells and batteries.

JUMP avionics leverage the commercial satellite industry, prior Constellation Altair work, Orion and Gateway, ISS, and the NASA Commercial Lunar Payload Services (CLPS) program. Avionics hardware is mounted to cold plates on the intertank between the propellant tanks.

The JUMP thermal loop leads from the cold plates to the GOX line between the LOX tank and the fuel cells. Heat exchangers use the thermal fluid to warm the GOX prior to fuel cell entry, thereby cooling the thermal fluid. This approach eliminates the need for radiators.

A capture system is used to join three core stages together in space. Definition of this system is forward work. As a starting design point, a three-stage capture system is envisioned. Soft capture is initiated with articulating (potentially magnetic) capture fixtures. A hard capture follows, analogous to the ISS Segment to Segment Attachment System [5]. Finally, structural capture is completed by means of an automated bolt driving system roughly analogous to an automatic version of the ET/Orbiter interface [6]. A critical analysis will be determining the dimensions and mechanisms of the bolt driving system and associated mass. It must be sufficiently robust to work without question, but each kilogram of mass is a kilogram of payload capacity lost.

Each core stage contains four landing legs, offset at 90 degree increments. The legs are configured such that when three core stages are mated the three legs not immediately adjacent to another core stage can deploy.

The JUMP lander does not have a true payload deck. Instead, an interface similar to a payload attach fitting (PAF) is used to carry the load from the payload to the lander primary structure. Each payload is responsible for structural, power, and data interfaces that can mate to the JUMP PAF. A design goal is that this same interface mates to both payload and launch vehicle, implying that the JUMP core stage is launched upside down.

A rough order of magnitude initial sizing for the JUMP lander is completed based on the liquid hydrogen starting point. The JUMP lander core stage is approximately 4.6 meters in diameter (including protrusions) and 8.36 meters tall, including the post-landing distance from the lunar surface (landing gear base) to the top of the PAF. Table 1 indicates the contribution of various components of the JUMP cores stage to its height and Figure 3 shows the approximate size of a single JUMP core stage inside a Falcon 9 launch shroud. The shaded rounded rectangle represents the gross height and diameter of the core stage.

Table 1. JUMP Core Stage Height Estimation

LOX Tank	1.01	m
Intertank	0.2	m
LH2 Tank	2.41	m
RL-10B-2	4.14	m
Landing Legs	0.5	m
PAF	0.1	m
Total Height	8.36	m

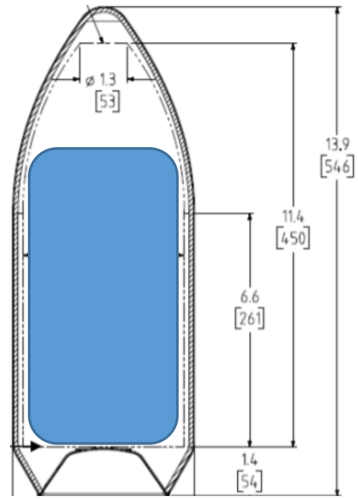

Figure 3. Approximate size of JUMP Core Stage in Falcon 9 Shroud

Rough order of magnitude estimates based on the rocket equation, shown in Equation 1, and using the RL-10B-2 engine with LOX/LH2 propellant suggest the single core JUMP lander can land slightly over 12.6 tons on the Moon while the triple core JUMP lander can land approximately 37.9 tons on the lunar surface. These estimates assume a mass fraction of 14% and boiloff rates of 1.5% per week for hydrogen and 0.2% per week for oxygen. The following Δv values are used: 0.829 km/s TLI to NRHO and 2.73 km/s NRHO to lunar surface. To account for additional uncertainty, a 15% reduction is applied to these estimates, thus a single core LOX-LH2 JUMP lander is estimated to be able to land 10.2 tons on the lunar surface, with a triple core JUMP lander delivering roughly 30.6 tons to the surface of the Moon. Lower specific impulse propellants will be expected to have reduced performance from these estimates. Use of tugs, would of course improve performance.

$$\Delta V = I_{SP} g_o ln \frac{m_o}{m_f}$$

Equation 1. The Rocket Equation

B. JUMP Lander Cargo Offloading

As an extremely tall lander, the JUMP lander requires an offloading system for cargo. While a sortie mission could be conducted with an embedded crew ladder or powered lift, large cargo delivery missions require pre-positioned offloading assets. JUMP-based lunar architectures include a variant of the Jet Propulsion Laboratory's All-Terrain Hex-Legged Extra-Terrestrial Explorer (ATHLETE) robot.

Developed under the Constellation program, the ATHLETE was envisioned as a 7-meter tall, six-legged walking/rolling robot that could split into two three-legged halves to straddle the 6-meter tall Altair lunar lander cargo deck to lift cargo from the vehicle. [7] A half-scale version was field tested under the NASA Desert RATS test series. The JUMP ATHLETE adds an additional 2.5 meters to each lower and upper leg segment, thus standing 12 meters tall when fully erect. The first cargo landing would include one or more ATHLETE robots, which would use their long legs to simply step off the lander and roll away. For future cargo missions, the ATHLETE(s) would autonomously offload the cargo and deliver it from the landing site to the outpost or other intended location. A secondary benefit of the ATHLETE is it can not only transport cargo, but can also lift and carry spent JUMP lander stages from one location to another, which will be useful in both landing site maintenance and future refueling and reuse operations.

C. JUMP Lander Operational Concept

The operational concept for any JUMP lander mission begins with a payload launch. The lunar surface payload is launched via CLV or SLS along with some form of service propulsion module to Cislunar space, where it will wait (presumably at or near the Gateway) for the JUMP lander to arrive.

Next, the core stage(s) launch. For a smaller payload (on the order of up to 10 tons), only a single JUMP core stage is required. For larger payloads (up to 30 tons), all three JUMP cores are required. The triple core scenario requires the launch of three CLVs in immediate succession, suggesting three operational launch sites capable of operating in parallel or a single site with very rapid turnaround capability. This is necessary to minimize propellant boiloff while waiting on subsequent core stages to launch. The goal is for the JUMP lander to have delivered its payload to the surface of the Moon within 14 days of launch of the first Core Stage.

The core stage is delivered to trans-lunar injection (TLI) by the CLV and it coasts until capturing itself into orbit near Gateway. In the case of the triple core scenario, the three core stages perform a rendezvous and then initiate the previously described three-stage capture sequence until the three core stages have structurally mated.

Next, the JUMP lander will rendezvous with the lunar surface payload. The lander will at this point mate to the payload. The lander and payload will then separate from Gateway and initiate a burn towards the Moon. It remains as a future trade to determine if the payload's service/propulsion module assists in this burn or if it undocks prior to Cislunar space departure. Finally, the lander will descend to the surface where an ATHLETE will unload the cargo from the lander and then return to reposition the lander to a storage location (e.g. a lander boneyard where landers will await future reuse).

Once a lunar surface in-situ resource utilization (ISRU) capability is operational on the Moon it will become a viable option to reuse JUMP landers. Refueled JUMP landers can deliver Earth return cargo, ascent stages, or even fueled JUMP core stages to Gateway. Those stages can potentially be refueled at Gateway via Earth-launched tankers, enabling repeated use of the JUMP lander. Initial landers, however, will likely instead be scavenged for spares or raw materials to use in establishing a surface outpost.

D. Moon to Mars Benefits

One of the key goals of human lunar activity is to pave the way for human missions to Mars. An important benefit for human Mars exploration is the JUMP lander enables the placement of habitats on the lunar surface similar in scale to those initially explored by NASA Mars Design Reference Missions (DRMs) and the NASA Mars Integration Group (MIG) for both transit and surface habitats. The DRMs and MIG have collectively explored both modular and monolithic habitat concepts, but in all cases the habitat masses would be challenging for a 5-9 mt lunar lander to deploy to the lunar surface. Increasing the capacity of a lunar landing system will better enable lunar habitats to represent the functionalities to be needed for long duration on Mars.

Further, the lunar payload delivery challenge being addressed by the JUMP concept is likely to also be faced by Mars mission planners. All of the challenges in delivering payloads to the lunar surface – Earth launch, in-space transit, descent and landing, and off-loading will be faced to a comparable or greater extent at Mars. Mars is further away from Earth than the Moon and has a higher gravity than the Moon. The largest propulsion systems in the current global industry are challenged to deliver landing systems to place payloads on the Moon. These same propulsion systems will deliver far less payload to Mars. Thus, the JUMP capability to assemble descent stages in space will be critical to deliver appropriately sized human systems to the surface of Mars. Current conceptual Mars landers such as the HIAD or Mid L/D might not be launched as integrated systems, but instead as component elements assembled at Gateway or in Mars orbit.

VI. Forward Work

The JUMP lander is at the initial stages of concept development, representing a Technology Readiness Level (TRL) 1. To advance the concept to TRL 3, four design trade cycles are needed, based on the following starting points:

1. Hydrogen Option: LOX-LH2, RL-10B-2 engine, conceptual RCS thrusters, cryocoolers, self-pressurization, intertank, PEM fuel cells, GOX thermal fluid;
2. Methane Option 1: LOX-CH4, HIAD engine, Morpheus RCS thrusters, cryocoolers, self-pressurization, intertank, batteries, GOX thermal fluid;
3. Methane Option 2: LOX-CH4, Morpheus engine, Morpheus RCS thrusters, cryocoolers, self-pressurization, conformal tank, methane fuel cells, GOX thermal fluid;
4. Hypergolic Option: MMH/N2O4, OMS engine, R4-D RCS thrusters, helium pressurization, conformal tank, ammonia thermal fluid,

Each trade cycle will include trajectory analyses, propellant tank sizing, engine sizing / selection, subsystems selection, core to core mating system mechanism design, payload attach interface design, landing gear design, MEL integration, cargo delivery capacity, CLV and launch site compatibility, and CAD integration. The design products of these cycles can then be compared to yield a recommended design configuration.

VII. Conclusion

The JUMP lander is an effort to overcome limitations in payload delivery to the lunar surface that trace back to Earth launch vehicle payload mass and volume capacities. Preliminary analysis suggests monolithic habitats and other large payloads previously thought to be beyond any ability to economically deliver to the Moon are in fact attainable within a JUMP architecture. Formal, funded study is recommended to more fully flesh out the performance capabilities of the JUMP lander and lunar surface architectures enabled by its use.

Acknowledgments

The author would like to acknowledge the innovative work of the NASA Jet Propulsion Laboratory, in particular the ATHLETE development team led by Brian Wilcox. Without the ATHLETE it would be extremely challenging to offload large payloads such as habitats, rovers, and logistics modules from the top of the JUMP lander. The author also offers acknowledgements of the Mars Integration Group, Lunar Surface Capabilities team, Human Landing System Formulation team, and prior incarnations of these teams dating back to the Apollo program. Finally, the author acknowledges Scott Howe and Hoppy Price of the Jet Propulsion Laboratory, who along with others, pursued conceptual modular lander work in 2016.

References

[1] Smith, M., “NASA Assessing Options to Speed Up Mid-to-Large Lunar Landers,” Spacepolicyonline.com, URL: https://spacepolicyonline.com/news/nasa-assessing-options-to-speed-up-mid-to-large-lunar-landers/, [retrieved 21 December 2018].

[2] Sloss, Philip, “Administration Proposes the end of EUS while Administrator considers full Exploration manifest rewrite,” NASAspaceflight.com, URL: https://www.nasaspaceflight.com/2019/03/administration-proposes-end-eus-exploration-manifest-rewrite/, [retrieved 26 April 2019].

[3] Börner, M and Manfletti, C, “Status and Perspectives of Laser Ignition of a Cryogenic Research RCS Thruster,” Space Propulsion 2014, Cologne, Germany, May 19-22, 2014, URL: https://www.researchgate.net/publication/262635873_Status_and_Perspectives_of_Laser_Ignition_of_a_Cryogenic_Research_RCS_Thruster/citations, [retrieved 21 December 2018].

[4] Falcon 9 Launch Vehicle Payload User's Guide, Rev 2, Space Exploration Technologies Corporation, October 21, 2015, URL: https://www.spacex.com/sites/spacex/files/falcon_9_users_guide_rev_2.0.pdf, [retrieved 21 December 2018].

[5] Cook, John, Aksamentov, Valery, Hoffman, Thomas, and Bruner, Wes, “ISS Interface Mechanisms and their Heritage,” AIAA Space Conference, AIAA, Long Beach, CA, 2011.

[6] Sivolella, Davide, To Orbit and Back Again: How the Space Shuttle Flew in Space, Springer Paxis Books, New York, 2014.

[7] Howe, A. Scott, Wilcox, Brian, “Outpost Assembly Using the ATHLETE Mobility System,” IEEE Aerospace Conference, IEEE, Big Sky, MT, 2016.