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Concept for a Crewed Lunar Lander Operating from the Lunar Orbiting Platform-Gateway

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Abstract

Lockheed Martin is working with NASA on the development of the Lunar Orbiting Platform – Gateway, or Gateway. Positioned in the vicinity of the Moon, the Gateway allows astronauts to demonstrate operations beyond Low Earth Orbit for months at a time. The Gateway is evolvable, flexible, modular, and is a precursor and mission demonstrator directly on the path to Mars. Mars Base Camp is Lockheed Martin's vision for sending humans to Mars. Operations from an orbital base camp will build on a strong foundation of today's technologies and emphasize scientific exploration as mission cornerstones. Key aspects of Mars Base Camp include utilizing liquid oxygen and hydrogen as the basis for a nascent water-based economy and the development of a reusable lander/ascent vehicle. At the core of Mars Base Camp is Orion, a highly capable vehicle with unique features designed for deep space environments and to keep crew members safe. The investments made in Orion can be leveraged to reduce the cost, complexity and development timeline for new crewed vehicles. The Gateway and Mars Base Camp can be designed to utilize the redundancy, performance, and safety built into Orion. Lockheed Martin has a long history of designing, building, and operating planetary landers from Viking to this year's InSight. A mission to study Mars' interior structure, InSight will answer key questions about the early formation of rocky planets. Given the current directives to enable long term deep space exploration, lunar exploration systems including landers should not be point solutions solely for the Moon. Just as the International Space Station is preparing us for long duration human spaceflight, lunar activities can prepare us for Mars. This paper will discuss the overall architecture for lunar exploration missions using precursor versions of the elements of the Mars Base Camp architecture. This includes the conceptual design, concept of operations, Orion derived systems, propulsion system trades, and the potential for a direct tie to Mars entry, descent and landing for a crewed lunar lander.

Keywords: Mars Base Camp, Gateway, Orion, Mars, NASA, Lockheed Martin

Acronyms/Abbreviations

ΔV = Velocity Change
COTS = Commercial Orbital Transportation Services
EVA = Extra Vehicular Activity
InSight = Interior Exploration using Seismic Investigations, Geodesy and Heat Transport
ISS = International Space Station
I_{sp} = Specific Impulse
ISRU = In-Situ Resource Utilization
LEO = Low Earth Orbit
LOX = Liquid Oxygen
LH2 = Liquid Hydrogen
MBC = Mars Base Camp
MADV = Mars Ascent/Descent Vehicle
MT = Metric Ton (1000 kg)
NASA = National Aeronautics and Space Administration
NRHO = Near Rectilinear Halo Orbit
NTP = Nuclear Thermal Propulsion
PPE = Power and Propulsion Element
SLS = Space Launch System
WDV = Water Delivery Vehicle

1. Introduction

IN 2016, Lockheed Martin introduced Mars Base Camp: a Martian Moon Human Exploration Architecture[1]. The Mars Base Camp (MBC) concept is a bold plan to transport scientists and astronauts from Earth to Mars orbit within about a decade to answer fundamental science questions and prepare for a human landing on the Martian surface. The key to achieving this vision is to capitalize on major architecture elements that are already being developed by NASA, Orion and the Space Launch System (SLS), in an innovative architecture that focuses on crew safety and high priority science objectives. Mars Base Camp includes the Mars Ascent/Descent Vehicle (MADV), which is a fully reusable, single stage vehicle, refueled in Mars orbit as a sustainable Mars exploration model, and the catalyst for water-based propellant generation and an emergent water-based space economy. [2]

The Gateway is an essential element for the assembly, logistics, and outfitting for reusable Mars transit vehicles. NASA has recognized the need for a lunar orbiting platform as a precursor to lunar and Mars human exploration missions and has rapidly formulated a program of record to acquire this capability.[3] The Gateway will be a logistics node and operations platform for lunar human exploration missions initially but is also entirely consistent with the development of missions to Mars.

Mars Base Camp will be assembled and outfitted at the Gateway and the transit configuration will return from Mars to the Gateway as a fully reusable vehicle system. Crews will re-fuel, refurbish and re-outfit the vehicle for the later missions. Although conceived for Mars, the reusable MADV is fully capable of lunar landings as a demonstration mission. Mars Base Camp shakedown missions are intended to demonstrate landing on the Moon prior to Mars expeditionary missions.

Lunar orbit and surface exploration is crucial in the path to Mars and will prepare us for Martian and beyond operations, just as the International Space Station is preparing us for missions outside of Earth orbit. While the Moon does not have an atmosphere like Earth or Mars, there is much to be gained by conducting science in lunar orbit and on the surface. Including Martian design requirements in the lunar exploration campaign will result in forward compatibility and the demonstration of operations before Mars missions. Performing missions to the lunar surface provides experience in terminal descent navigation, guidance, and propulsion; ascent operations; and Extra Vehicular Activities (EVA) on the surface.

The Gateway and the lunar lander will also provide valuable insight into deep space logistics and experience living and working in a deep space environment. The lunar lander concept described in this paper follows the key tenets of the MBC mission and is on a direct path to the Mars Base Camp Ascent/Descent Vehicle. This precursor design follows the MADV design concept, but is at a smaller scale for lunar operations, and it removes the aeroshell given the lack of a lunar atmosphere. Each lunar lander mission will lay the groundwork for the next and reusability provides affordability through avoiding expendable modules. The design will leverage existing systems and technologies to the greatest extent practical to reduce development costs and risks. The architecture embraces and leverages international and commercial roles and partnerships. Figure 1 shows a concept of the lunar lander.

Lunar economic activity can play an expanding role in future deep space missions. The architecture described here deliberately involves NASA infrastructure and investment to encourage a water-based economy that can extend to in-situ resource extraction and utilization of lunar polar ice deposits. These concepts are critical in the ability to conduct planned missions to Mars.

The purpose of this paper is to show how precursor versions of the elements of the Mars Base Camp architecture can be demonstrated during a lunar exploration campaign, and how the architecture can benefit both lunar and Mars exploration. The importance of the lunar Gateway to sustainable exploration will be shown, as well as the tie to similar operations in Mars orbit. The aspects of lunar exploration that will benefit future Mars exploration campaigns is described. The design concept for a lunar single-stage, reusable lander, and the support infrastructure for refueling is explained. And finally the importance to deep space exploration of an eventual commercial, water-based economy for propellant production is shown, starting with lunar exploration.

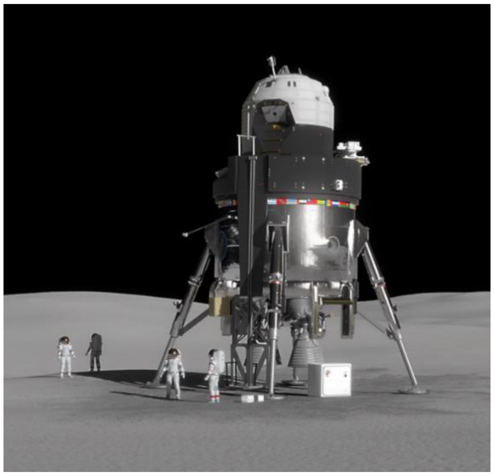

Fig. 1. Mars Base Camp Precursor Lunar Lander

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2. Importance of the Gateway for Sustainable Deep Space Exploration

The U.S. administration's updated space policy, Space Policy Directive 1, directs NASA to "lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system." The Gateway is the fastest, most cost-effective option for creating a sustained lunar presence, leveraging reusable vehicles. From this orbital platform, we can begin to explore the surface of the Moon with a reusable lunar lander. After a surface mission, it returns to the Gateway, where it can be refueled and serviced, and then kept in orbit until the next surface sortie mission. The Gateway's Near Rectilinear Halo Orbit (NRHO) provides global lunar access for a lander.[4] Having the ability to visit multiple sites, while still having a reusable lander, supports many international, commercial, and scientific communities. Power, propulsion, and communication relay is handled by the Gateway once there. The Gateway also is an orbital safe haven for any required lander aborts.

Reusable lunar landers would be much larger, more complex, and more expensive without the support of the Gateway, which is a concern for a crew vehicle performing a dynamic phase of flight. Separating the functions of Earth ascent, transit, and entry (Orion); permanent orbital flight and resupply support (Gateway); and landing and short-term surface stays (lander) reduces the complexity of the modular systems, provides for more versatility for different missions, and increases safety by providing for contingency options. The prime functions of the Gateway do not require a large and complex vehicle. A few simple modules are all that is required. Figure 2 shows Lockheed Martin's concept for the Gateway with the lander docked.

The Gateway simplifies overall propulsion requirements, allowing for multiple commercial and international partners to support. Cargo, crew, and

Fig. 2. Lunar Lander at Lockheed Martin's Concept for the Gateway

Gateway elements only need enough capability from their launch vehicle to be delivered to lunar orbit. The lander only needs enough capability to bring a crew and some cargo to the surface, not large pieces of infrastructure. Global lunar access is key to making lunar exploration long-term and sustainable. With an orbital platform, the infrastructure is in a flexible location and provides valuable insight into landing sites for future missions.

In addition to human surface missions, there is possibility for constant telerobotic presence on the Moon. Lunar night is a major technical challenge for human landers, but a robot could be telerobotically operated by the crew at the Gateway, in real-time during the lunar night. Robotic assets could also be left to operate autonomously for long periods of time. Real-time control from the Gateway would dramatically increase the body of knowledge about all regions of interest, expanding the potential commercial market while also narrowing down the locations that are viable for a permanent surface settlement.

By initiating lunar exploration from an orbital platform, the lander's critical path is separated from the existing exploration architecture. If the development schedule of a human rated lander is delayed, exploration missions (such as telerobotic missions) could still be carried out using the existing Gateway elements and Orion. The Gateway becomes a hub for international science and partnership.[5] It also becomes a commercial opportunity for cargo resupply and logistics. This approach achieves the vision of creating a sustainable lunar architecture with international and commercial partners. Without this permanent infrastructure, lunar activity, especially commercial activity, is limited. It is crucial that the government pave the way for permanent infrastructure, like the interstate highway system in the past. Providing permanent infrastructure is necessary for commercial activity to begin and to be sustained. Committing to this architecture and vision will signal to commercial and international partners that the U.S. is intent on starting deep space exploration and investing in the earliest necessary pieces.

As we venture past the Moon and on to further deep space destinations, including Mars, the same approach can be used. Committing to the gravity well of a planetary body is costly and difficult. Once you have landed assets and infrastructure in one location, it takes tremendous amounts of energy to move to a new location. A period of orbital missions and landing sorties before choosing a single location for landed infrastructure will have many benefits. We will arrive in orbit, use telerobotics and astronaut scientists to evaluate the many candidate landing sites, learn about the in-situ resources and environment, before venturing to the surface from the orbital platform. If something goes wrong on the way to the surface or on the surface, there is a safe haven in orbit We have mastered living in orbit aboard the ISS, and now we have the opportunity to use this knowledge at the Moon, Mars, and beyond.

3. A Lunar Exploration Architecture that Paves the Way to Mars

Lunar lander missions and lunar exploration systems cannot simply become a point solution for the Moon. Just as the ISS is preparing humanity for reusability and missions in deep space, lunar lander missions and a lunar Gateway are crucial to prepare for Mars. Utilizing that experience in the challenging environment of a dynamic mission to the Moon will bring us closer to conducting future missions to Mars. The goal of lunar landing missions, then, will be twofold:

1. Conduct valuable operations and collect data that will help to decrease the cost and increase effectiveness of future missions to Mars.

2. Develop the platforms and skills necessary to get to Mars.

The benefits of performing lunar missions using a Gateway and a lander greatly expand our ability to provide experience and data to help drive efforts towards Mars. Although the Moon does not have an atmosphere or gravity like that of Earth and Mars, there is still much to be learned from working in the challenging environment of the lunar surface. Performing lunar lander missions will not only provide data, but it will also provide experience conducting the critical operations necessary of a Mars mission, such as operating a vehicle and refueling in orbit.

The goal of using long duration cryo-propulsion systems will aid in understanding how to maintain and operate a mission to Mars that utilizes similar systems. Operating the vehicle will provide valuable operational experience utilizing the propulsion systems that will be necessary for landing on the surface of Mars, as well as launch/return/rendezvous with the orbiter from the surface.

In addition to the propulsion and fuel elements of the lander missions, operating the lander will provide valuable experience in terminal descent navigation and vehicle guidance systems. The ascent portion of the mission also will have parallels to Mars ascent, including deep space rendezvous, abort options, and crew tasking. Figure 3 shows a MADV demonstration mission on the surface of the Moon.

Lunar missions will have a large influence on how we develop Mars missions since it greatly expands our capabilities to live and work on another planetary body. The final Mars exploration systems will likely be a combination of systems that are identical to lunar systems, and those systems with lunar heritage but which need to be different to handle the differing environments. Extra-vehicular activities will be conducted on the surface of the Moon using the lunar lander. Although there is no atmosphere and the dust has different characteristics, critical operational procedures and many systems can be developed using the lunar surface as testing ground. Also, utilizing a lunar platform to better understand long duration crewed missions in space is important for preparing for missions to Mars.

The logistics of supporting landing missions require systems development and operational experience that is more challenging than low Earth orbit logistics. Lunar logistics will be the first leg of a Mars exploration logistics campaign. Living in deep space for an extended time, working outside of Earth's magnetosphere, and understanding how these operations will differ from the ISS will help us to more deeply understand what is involved in conducting missions to Mars. Additionally, lunar lander missions will start to add some communication link delays to Earth.

Fig. 3. MADV on the Moon

4. Design Concept for a Sustainable Lunar Exploration Architecture

In considering a Moon and Mars exploration architecture that is sustainable, based upon reusable elements and involving commercial propellant and cargo delivery services, liquid oxygen (LOX) and

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liquid hydrogen (LH2) become the propellants of choice for two primary reasons.

First and foremost, only LOX/LH2 provides the performance required for a single stage lunar lander operating from the Gateway orbit, where the round trip ΔV is in excess of 5000 m/s. Sustainability requires full reusability, and while it is possible to have a fully reusable two stage system, the additional cost and complexity of a two-stage system is significant. It is conceivable that a single stage LOX/methane lander could be developed, but the mass fraction required implies very lightweight systems, which further imply an increase in technology, cost/risk, and potentially a loss of reliability with respect to margins, factors of safety and/or redundancy.

Second, water uniquely provides the ubiquitous resource that leads to sustainable space exploration and human expansion, simultaneously providing humans and plants the key ingredient for life, while also providing the highest performance chemical propellants from a single compound that is easy to extract, refine, transport, transfer and store. Sustainability depends on commercial involvement and creating an economy that intentionally advances water as the key commodity launches this economy in the most equitable and deliberate way possible. With the government purchasing large quantities of water, by the gallon in support of exploration, the commercial marketplace for space transportation and applications has a stable framework to foster investment and development. A commitment to declaring water the essential commodity that drives human exploration effectively lays the tracks for a space-based economy. Ultimately, it is expected that a self-sustaining economy of fuel production from water will develop to support satellites, science, and exploration in future missions with multiple providers existing to supply the government, commercial, and international partners.

LOX/LH2, with a specific impulse (I_{sp}) greater than 450 seconds, is clearly the lowest wet mass chemical system for any given dry mass payload. It could be argued that the extra propellant mass needed for LOX/methane, with an I_{sp} > 360 sec, could be a competitive alternative considering its higher density and higher storage temperature. For this lander design, the difference in the total mass of propellant between hydrogen and methane is 35 MT. The additional mass to store liquid hydrogen would not be nearly as large as the propellant mass difference.

It is the combination of high I_{sp} and the availability of water throughout the solar system, including the Moon, that drive the selection of LOX/LH2. NASA and industry have a large and ongoing investment in LOX/LH2 propulsion systems including the core and upper stages of the SLS, and multiple commercial upper stages. NASA should lead the development and demonstration of the technologies and systems necessary to realize the water-based economy. The ability to refine, store and transfer propellants in space is not trivial, and LH2 production and storage in particular present unique challenges. However, these are straight forward engineering problems with straight forward solutions that simply need focus to accomplish.

Given this, a long-term sustainable lunar exploration architecture consists of the following major elements:

1. Fully reusable, single stage crewed lander powered by LOX/LH2 (see fig. 4)
2. Commercial exploration launch and transportation systems capable of delivering upon demand:
    - Cryogenic propellant
    - Crew mission consumables
    - Crew mission cargo and equipment
    - Bulk water for refining
3. A co-orbiting propellant storage and transfer facility in the Gateway orbit
4. A co-orbiting propellant production facility in the Gateway orbit, a LOX/LH2 refinery

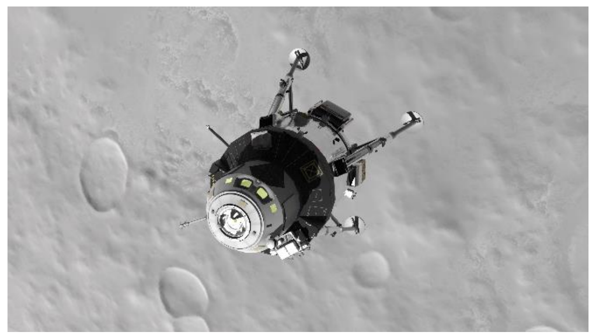

Fig. 4. Single-Stage, Reusable, Mars-Precursor Lunar Lander

4.1 The Lander

The key attributes for this single stage, fully reusable crewed lunar lander are:

- Capability of delivering a crew of up to 4 from the Gateway to the lunar surface
- Capability of delivering 1 metric ton of payload to the surface per mission
- Capability of operating on the surface for up to 2 weeks
- Capability of returning the crew to the Gateway without maintenance or refueling while on the surface
- Total ΔV capability of 5 km/s

A single stage lander, besides being feed forward to Mars and the Mars Base Camp concept, allows for the simplest vehicle design that includes full reusability. A capability of 4 crew matches Orion's capability, allowing all of the crew to visit the surface. It also matches NASA's current planning for Mars crew size. One ton of payload is a minimal amount of payload to allow for scientific equipment for the crew to use and leave behind, and perhaps a small unpressurized rover. The lander is sized for a two-week total duration to match the design for the MADV, and to account for a stay of a duration near one lunar day. By operating out of orbit instead of requiring surface infrastructure, initial crew sortie missions can address science objectives in multiple locations and confirm the placement of infrastructure like ISRU equipment. A ΔV capability of 5 km/s covers the round trip between the Gateway and the surface.

Access to the lunar poles as well as lower latitude sites both on the lunar far side and near side are essential, but landing site locations, local solar times, and surface stay durations should not be over constrained.

The lander is an aggregation and evolution of existing systems and capabilities. The crew pressure vessel is based on a lightweight version of the Orion structure components, which can be tailored and optimized for lander design drivers where launch abort and water landing loads are not dominant. The avionics systems, life support systems, controls and displays, and crew systems are common and interchangeable with Orion. This degree of commonality supports safety while leveraging existing deep space human rated systems in the most cost-effective way possible.

The two-tank LOX/LH2 cryogenic propulsion system reflects the background with the Centaur upper stage and its descendants. One possible technology for the main engines are RL-10 derivatives with deep throttling capability as demonstrated during the Delta Clipper program. Four engines were selected to provide engine out capability. A three engine solution would have had difficulty with off-axis thrust with one engine out. This ensures that there are no black zones in descent or ascent, and that a self-powered abort to the Gateway safe haven is always possible.

The wet mass of the lander is 62 MT, with a dry mass of 22 MT. Figure 5 shows multiple views of the lander. Lockheed Martin's experience with propulsive descent Mars landers, including Viking, Phoenix and InSight, helps prepare us for lunar landing.

4.2 Commercial Exploration Launch and Transportation Systems

Initial delivery of the cryogenic propellant required for the first lander mission may consist of a single launch or multiple launches. The commercial logistics systems may be expendable or may be designed or evolve to be reusable. The commercial launch industry is already pushing towards re-usability. NASA anchor tenant support for propellant purchases will result in an increase in the commercial launch rate that can help accelerate these advances.

One method of propellant delivery, consistent with space tug concepts developed in the past, would involve a fully fueled tug stage rendezvousing in Low Earth Orbit (LEO) with a fully loaded propellant container. The tug would deliver the propellant to the Gateway orbit and return to LEO to be refueled.[6]

Fig. 5. Multiple Views of the Lander

Whether the propellant storage and transfer facility is delivered to the Gateway empty, partially loaded, or fully loaded can and should be left up to commercial competitive solutions. NASA purchases of services may include or may separately address exploration consumables, maintenance, mission unique equipment, and other cargo elements traveling to the Gateway. That cargo may include the delivery of the LOX/LH2 refinery. Other LOX/LH2 refineries may spring up in locations other than the Gateway orbit in support of commercial and government cislunar spaceflight.

4.3 Propellant Storage and Transfer Facility

Figure 6 shows a concept for the propellant storage and transfer facility. The tankage system includes a cryostat which radiates to deep space, minimizing boil off and the electrical power required to maintain cryogenic fluids.

The facility has the capability to maintain station keeping or to be the active vehicle in an autonomous deep space rendezvous and docking maneuver sequence. The cryogenic storage tanks are sized to support a single lander sortie mission with reserve, but also account for losses inherent in cryogenic conditioning and transfer. The facility may make use of a copy of the Power and Propulsion Element from the Gateway to efficiently maintain orbit or transfer to other lunar or cis-lunar orbits, while providing power and attitude control.

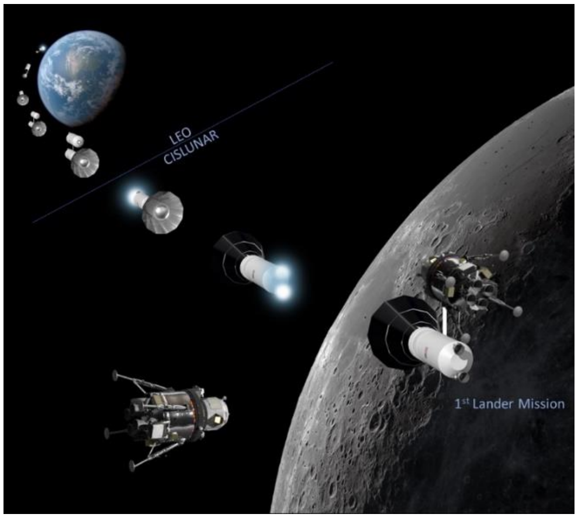

Fig. 6. Propellant Storage and Transfer Facility

4.4 The Propellant Refinery

The ability to create rocket fuel from solar energy and water is nothing less than transformational. LOX/LH2 chemical propulsion has over 450 sec of I_{sp} and paves the way for hydrogen powered Nuclear Thermal Propulsion (NTP) systems with I_{sp} in excess of 900 sec. There are many significant technical challenges involved in mastering the production and use of cryogenic oxygen and hydrogen in space, but the collective experience in using liquid hydrogen as a fuel for spaceflight successfully since the 1960s demonstrates viability. The refinery produces LOX/LH2 from water delivered commercially from Earth and/or in-space sources using large solar arrays as the power source. This includes the liquification of the propellants and transfer to a separate or integrated propellant storage and transfer facility. Figure 7 shows a concept for the refinery.

It should be pointed out that water naturally occurs with an oxidizer to fuel mass ratio of 8:1, while conventional LOX/LH2 engines burn at a ratio of 6:1 (even though this is less than stoichiometric, the lower mass density exhaust actually produces peak I_{sp}). This implies that more water by mass will be required compared to delivering cryogenic hydrogen and oxygen in the 6:1 proportion. This results in a significant excess production of oxygen. Perhaps a very good use for the excess oxygen will be found. Certainly, it is breathable and usable in other chemical reactions, or perhaps higher mixture ratio engines will be made to operate at a slightly lower I_{sp}.

5. Logistics Design and the Water Economy

The creation and use of the Gateway as a logistics node can be a part of a far reaching and sustainable human exploration and expansion architecture. The Gateway logistics node is not essential for a return to the Moon in an expeditionary fashion, but it is crucial for a sustainable human exploration strategy with key elements including:

- Reusability
- Commercial services and public/private partnerships supporting NASA
- Separation of elements by complexity, cost, and crew, where NASA leads the development of new technologies, expensive infrastructure and safety critical systems

These elements are the logical consequence of the guiding principle of expanding human presence into space, translated to policy imperatives to involve private and commercial interests from the start. Lockheed Martin supports this vision where NASA leads in a sustainable quest to further human knowledge and expand the limits of human capability. The architecture described in this paper converts space policy into a specific plan, and to map existing, planned, and potential human space flight systems into a coherent and executable framework.

Orion was designed to support deep space exploration and offers the most cost-effective source of human rated systems when considering lunar landings and operations to and from the Gateway. The ability

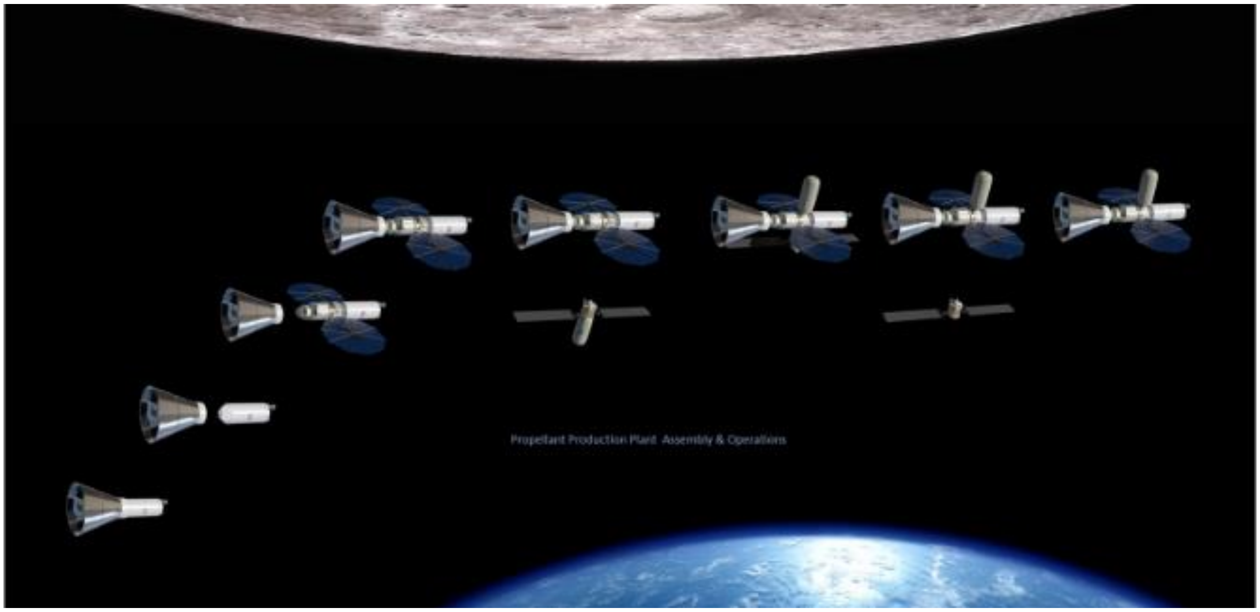

Fig. 7. Propellant Refinery

of Orion to serve as a crew transportation system, command deck, rescue vehicle, safe haven, and basis for the derivation of compatible systems, elements and modules is critical to applying development resources to unique items required for landing.

The role of SLS in the architecture is to transport items of extremely high value, including crew members and expensive integrated systems. These consist primarily of dry mass items contributed by NASA and other international partners. Commercial exploration launch and transportation systems supply services and commodities which facilitate and enable the establishment, resupply and operation of the high value assets emplaced by SLS. The inherent segregation of risk based on value allows commercial entities to propose options to NASA based on a wider range of cost/risk/reward models.

For NASA's Commercial Orbital Transportation Services (COTS) program, this strategy has proven to be successful and resilient to failure. Commercial vehicles are ideally suited to deliver lower value supplies including consumables, maintenance items, science equipment and other mission essential items. The Gateway will require all of these items for initial operations and re-supply.

However, there is one major difference between low earth orbit and deep space operations. By far, the largest commodity necessary to sustain lunar landings or the exploration of Mars is propellant. For spacecraft systems operating in deep space, propellant makes up 60% or more of the wet mass of the system. For these high value, SLS-delivered systems to be made reusable and sustainable they must be refueled, and propellant becomes ever more the dominant resource.

The concepts of in-space propellant generation, storage and transfer are not new. These concepts remain viable but are unlikely to be realized without a space policy which moves beyond their perceived cost and risk. Space policy that seeks to both advance human exploration and provide an expanding envelope for commercial endeavors in space must embrace the notion that the largest component of deep space exploration is propellant. Propellant as a commodity must be supplied by commercial partners.

Because of the high ΔVs associated with deep space operations, and the objective of reusability as essential to sustainability, liquid oxygen and liquid hydrogen are the most effective propellants. These components may be derived from water, the most ubiquitous resource in the solar system. Because it is also essential for breathing, drinking, plant growth and long-term viability of human populations, the commercial delivery of water will become a highly competitive industry sector. In a pay-by-the-gallon model, industry players are free to develop, evolve or optimize their own launch and delivery systems while providing NASA with more and more cost-effective options for refueling their reusable fleet spacecraft, thus concurrently advancing the overall sustainability of NASA's programs while lowering barriers to further commercial activity.

With water as the only payload, launch insurance and payload integration costs will be minimal. A hugely competitive market can develop at any primary or secondary lift capacity. The drive to minimize cost to the Gateway per kilogram of water delivered may open the way for competing sources of water supply to

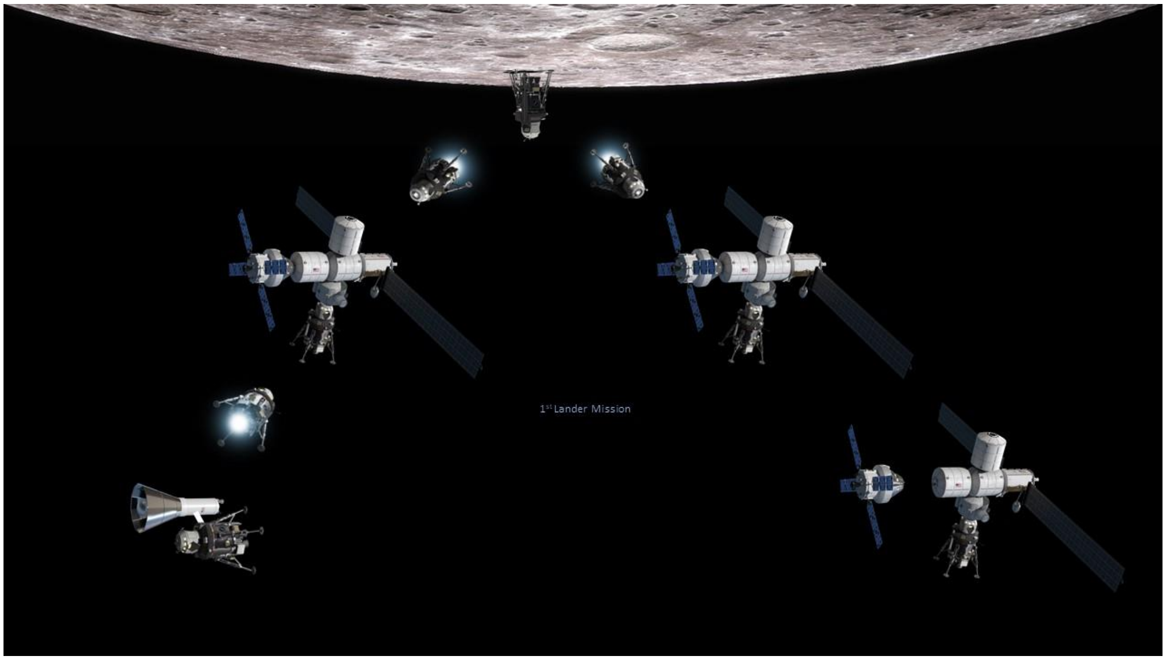

Fig. 8. First Landing Concept of Operations

develop. These may include the lunar poles, asteroids or other in-space resources.

However, the first human landing since Apollo 17 does not have to depend on the realization of in-space propellant production from water. The delivery of LOX/LH2 refined on Earth can be employed until a space-based refinery at a Gateway logistics node can welcome water deliveries. Figure 8 shows a concept of operations for the first landing.

The path from refinement of water into LH2 is also consistent with future technology, including Nuclear Thermal Propulsion. The radical leap forward in high-I_{sp}, high-thrust propulsion associated with nuclear thermal propulsion could bring much more of the solar system within reach of human explorers and entrepreneurs.

6. Conclusion

With the policy in place to enable long term deep space exploration beyond LEO to Mars and beyond, lunar exploration systems can't be point solutions for the Moon. Just as the ISS is key to developing the systems and operations knowledge for deep space, lunar activities will prepare us for Mars. While there are environmental differences between the Moon and Mars, such as the lack of a lunar atmosphere and the differences in gravity, there are still many things to learn from lunar missions and many of the technologies required apply to Mars as well. In order to gain the most benefit, the lunar exploration campaign and systems must be planned to maximize commonality to Mars exploration. Gaining operations experience in a challenging environment and for a dynamic mission reduces the risk to Mars missions. The Gateway is a logistics node and space dock for both lunar surface operations and Mars missions.

This concept study shows a design for a precursor vehicle on a direct path to the Mars Base Camp Ascent/Descent Vehicle. This precursor design follows the MADV design concept, but is at a smaller scale for lunar operations, and it removes the aeroshell given the lack of a lunar atmosphere. The design preserves full reusability, the single stage design, hydrogen/oxygen propulsion, Orion systems, and refueling in orbit. The key MBC tenets are kept, including:

- Each mission lays the groundwork for the next.
- Reusability is key to affordability.
- Existing systems and technologies are leveraged to the greatest extent possible.
- Crew safety and reliability is paramount.
- Partnerships between NASA, international, and commercial contributors are fostered and embraced.

Perhaps even more important than the lander itself, the infrastructure required to support the lander such as the Gateway, cargo systems, and propellant storage, transfer, and water refining facilities lay the groundwork for sustained exploration of the lunar surface and Mars.

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