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Crewed Lunar Landing Mission Campaign from the Gateway

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Abstract

Lockheed Martin has a long, successful history of designing, building, and operating spacecraft and landers for deep-space applications, from the first successful Mars lander mission by Viking I in 1976 to three orbiters and one lander that are all currently studying Mars and relaying surface communications. Lockheed Martin is working closely with NASA, the international aerospace community, and other aerospace companies to help develop an optimal architecture for supporting humans at the Moon. Lockheed Martin is the prime contractor for Orion and has been developing concepts for the Gateway along with concepts and technologies for the Human Landing System (HLS) under contract to NASA. The Gateway will be positioned in the vicinity of the Moon to serve as the key piece of infrastructure that enables reusable Lunar landers and sustainable exploration of any location on the Lunar surface. As a Commercial Lunar Payload Services (CLPS) program provider, Lockheed Martin is ready to deliver Lunar science and commercial payloads to the Moon. Deep-space human exploration requires a unique set of advanced, flight-proven systems, with the crew and vehicle operating in autonomy. NASA has announced an HLS architecture and is planning Lunar sortie missions from the Gateway, transporting astronauts to the Moon's surface by 2024. This paper will describe a proposed early mission campaign for crewed landings, including those objectives focused on science, exploration, and technology development. Beyond the major contributions of the crewed landing missions, a Lunar infrastructure comprised of CLPS, Orion, SLS, Gateway, HLS, and various logistics vehicles opens a whole new set of opportunities for secondary science, commercial payloads, and exploration for expansion into deep space. Last year, Lockheed Martin presented a reusable, single-stage lander design, an initial concept for delivering humans to the Lunar surface and a precursor to the Mars Base Camp Mars Ascent/Descent Vehicle. This year, a multi-stage Lunar lander concept will be described, one that leverages both Lockheed Martin's human-certified spacecraft and our deep-space vehicle design, development, and operations experience. Those investments in Orion and interplanetary spacecraft will drive significant reductions in the cost, complexity, and development timeline associated with new crewed vehicles. As the international community returns humans to the Moon and on to Mars, Lunar exploration must proceed with Mars in mind and develop feed-forward platforms and hands-on experience.

Keywords: Orion, Artemis, CLPS, Gateway, Human Landing System, Moon, Mars Base Camp, Lockheed Martin

Acronyms/Abbreviations

AE = Ascent Element
CLPS = Commercial Lunar Payload Services
DE = Descent Element
EVA = Extravehicular Activities
HLS = Human Landing System
ISRU = In-Situ Resource Utilization
LEO = Low Earth Orbit
LLO = Low Lunar Orbit
MBC = Mars Base Camp
MADV = Mars Ascent/Descent Vehicle
NRHO = Near Rectilinear Halo Orbit
PPE = Power & Propulsive Element
PSR = Permanently Shadowed Region
TLI = Trans Lunar Injection

1. Introduction

NASA's goal 50 years ago was to land humans on the Moon and return them safely to Earth. The goal today is to send humans to the Moon by 2024 in a sustainable way with international and commercial partners to prepare for the next giant leap towards Mars. The same core technologies that enable Orion to safely transport humans farther than any other vehicle in existence are also needed for a human lunar lander. Leveraging existing NASA investments provides an affordable and credible path to send the next astronauts, including the first woman, to the Lunar surface. At the same time, the upcoming campaign cannot offer point solutions for the Moon alone. Making elements of Lunar orbital and surface exploration forward-compatible reduces the cost, complexity, and development timeline of future Martian missions.

The following paper describes how an Orion-based HLS architecture can interact with the Gateway and precursor Commercial Lunar Payload Services (CLPS) missions to do more than was ever possible in the Apollo era. Each surface mission builds off the last, building up capability to the point where extended Mars preparations, Lunar science, and economic development can take place.

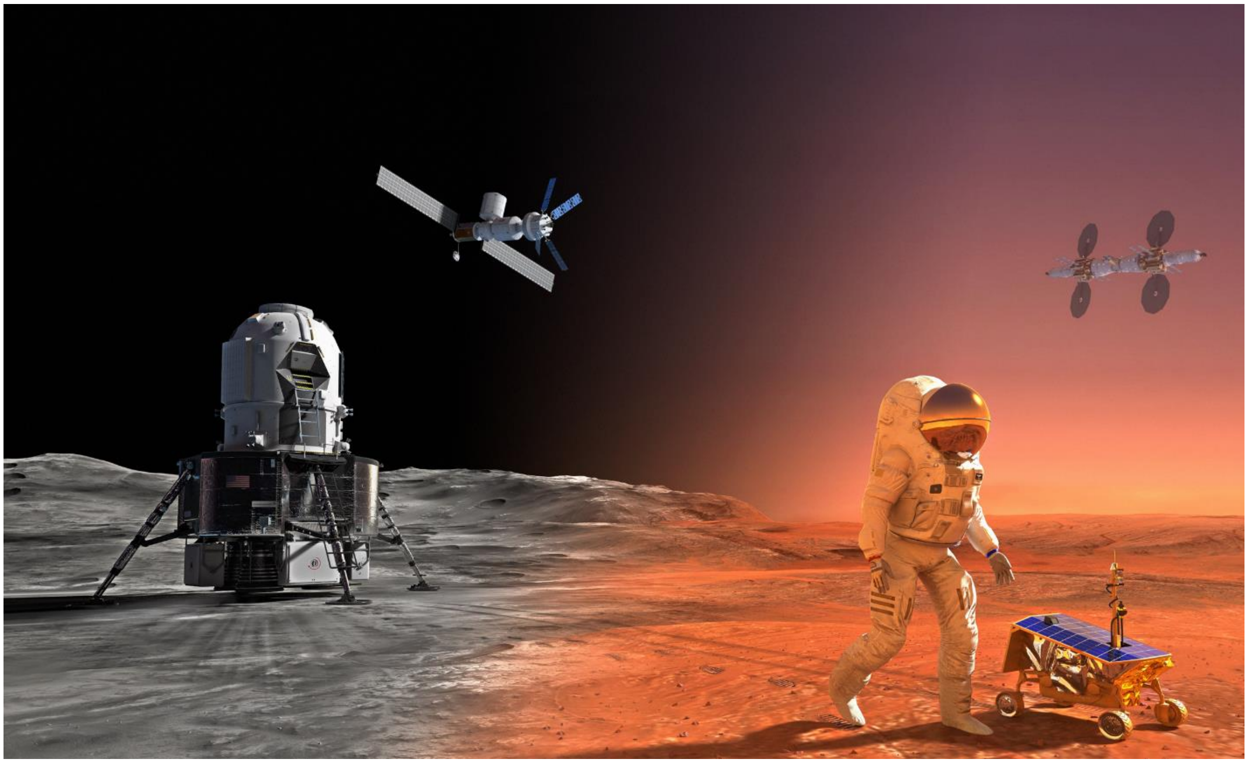

Figure 1. An artistic vision for Lunar and Martian human exploration. The next orbiting and surface missions at the Moon will feed forward to the first human presence on Mars in a sustainable campaign.

2. Proposed Lunar Mission Campaign

This year, the U.S. Administration took a bold step by advancing the timeframe in which astronauts will return to the Moon from 2028 to 2024. In the nearly six months since the announcement, NASA and commercial partners have made great progress towards that goal. Elements already in development have completed major milestones, such as Orion's Ascent Abort-2 (AA-2) test on July 2, 2019 (see Figure 2). Furthermore, contracts for the first two Gateway elements have been awarded, with Human Landing System (HLS) soon to follow. These rapid developments showcase a sense of urgency and commitment to the 2024 goal. The following Lunar exploration campaign builds on this manifest for rapid progress. A multi-element architecture consisting of Orion, the Space Launch System (SLS), Gateway, robotic CLPS landers, and HLS provides the tools needed to harness the Lunar frontier and move forward to Mars. Considering the vast spin-off technologies provided by Apollo, from modern athletic shoe designs to special kidney dialysis machines, it is no stretch to imagine the return on investment will be even greater for people on Earth today.

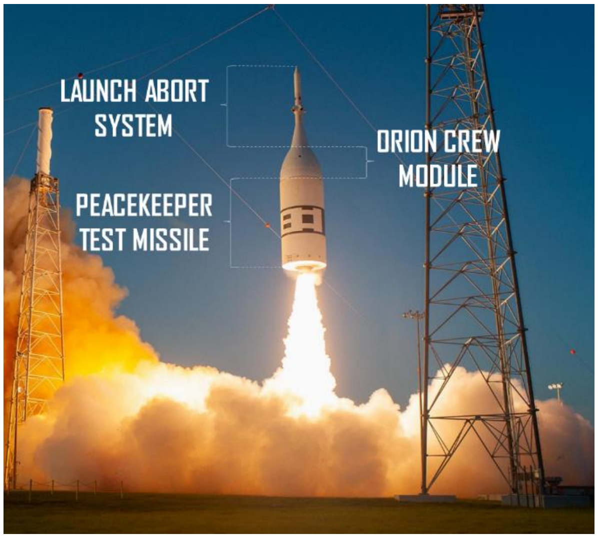

Figure 2. The AA-2 Flight Test successfully demonstrated Orion's Launch Abort System, designed to quickly separate the Orion Crew Module from the launch vehicle in emergency scenarios. *Photo credit: NASA*

2.1 Artemis 1 – NASA's Orion Returns to the Moon

The next Lunar exploration campaign begins with Orion, which will travel to the Moon and back without crew, testing the European Service Module on its first flight and the second crew module re-entry, descent, splashdown, and recovery. Artemis 1 also includes a secondary manifest of external and internal payloads. As Orion approaches the Moon, 13 small satellites will be deployed externally from SLS to collect deep space data and demonstrate technologies critical for future human exploration missions. Lockheed Martin's LunIR CubeSat is among the 13 selected and will perform a Lunar flyby to collect sensor data that will enhance our knowledge of the surface and inform future endeavours. Spare volume inside Orion's Crew Module will play host to a suite of scientific instruments and technology demonstrations, such as the Astrorad® vest, **Error! Reference source not found.**. For humans to survive long duration stays on the Moon and Mars, the health impacts of deep space cosmic radiation must be better understood and mitigated. The Astrorad® vest promises to shield astronauts from harmful radiation once they travel beyond Earth's magnetic field, which protects humans in LEO [1].

2.2 Artemis 2 – U.S. Astronauts Return to Deep Space

The Artemis 2 mission will feature a fully outfitted Orion spacecraft designed to test the world's only deep space exploration system. Now complete with crew systems, life support systems, and consumables, Orion will transport astronauts on a flyby trip around the Moon. During this flyby, astronauts will be at the farthest distance from Earth ever travelled in human history.

Figure 3. The AstroRad Vest provides radiation protection for Astronauts beyond Low Earth orbit. It is being tested on Artemis 1 and the ISS for ergonomics and performance. *Photo credit: StemRad*

2.3 CLPS Landers to Support Future Artemis Missions

The Moon is comprised of many resources which can be harvested, processed, and used to support humans on the Lunar surface. While scientists have learned much from previous missions about water ice and other volatile resources, there are still unknowns in how and where these resources exist and as well as how easy or difficult it will be to access them. In order to further understand and characterize the Moon, both on and below the surface, NASA will execute scouting missions determining the best locations for resource extraction. These missions will also accomplish much more science than just resource identification, including collecting geologic data, volcanic deposit and impact evidence, and even radio frequency astronomy on the far side of the Moon where Earth emissions are blocked. Some key science questions that will be addressed are:

- How does bombardment at the Moon illuminate Solar System evolution?
- What is the Moon's past and present geologic history?
- Where and how deep is the water on the Moon located?

Over a series of missions, CLPS landers, as seen in Figure 4, will deliver rovers and scientific equipment to achieve all of these objectives. Each lander is designed to offer a range of down-mass capabilities. The LM McCandless lander offers capabilities at the high end of CLPS landers [2]. From CubeSats deployed in low lunar orbit (LLO) to small rovers delivered via CLPS landers, these vehicles will precede human landing missions to identify locations for habitat landing sites as well as detect resource rich areas critical for sustaining humans for long durations on the Lunar surface.

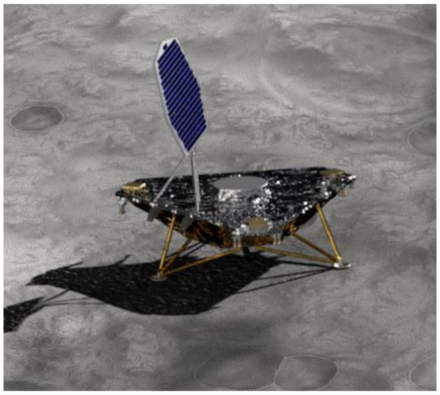

Figure 4. The Lockheed Martin McCandless Lander, part of NASA's CLPS program, can deliver rover and other science payloads to the Lunar surface.

2.4 *Artemis 3 – Humanity's First Steps at the Lunar South Pole*

The third Artemis mission will deliver two astronauts to the Lunar south pole, including the first woman to step foot on an extra-terrestrial body. The areas near the Shackleton crater, at the Moon's south pole, are a likely first landing location.

The HLS will be comprised of several elements depending on the final designs, such as an Ascent Element, a Descent Element, and perhaps even in-space Transfer Elements or Refuelers, which will be aggregated at or near the early Gateway, in the Near Rectilinear Halo Orbit (NRHO). Initially the Gateway will consist of a Power and Propulsion Element (PPE) and a small pressurized module. Once HLS is aggregated and ready, Orion will bring the astronauts to the Gateway where they will check-out, ready, and board the lander. HLS will then transit from the Gateway to the Lunar surface.

Figure 5. An illustration of the early Gateway assembly residing in NRHO, where Orion has been docked during the Artemis 3 mission. The AE has arrived back from the Lunar surface, filled with rocks and regolith from the Moon for transit back to Earth for further study.

Two astronauts will reside on the Lunar surface for 6.5 days to conduct extravehicular activities (EVAs), while the remaining Artemis 3 crew members will remain onboard Gateway to maintain communications, perform deep-space science objectives, and complete other mission objectives. While at the Lunar south pole, astronauts will execute science-focused tasks and collect approximately 100 kg of regolith and rock samples for further analysis back on Earth. The crew will use EVA tools to extract scientifically significant Lunar samples. Analysis of these samples will be critical to NASA and the science community for understanding the origins of the Earth, its Moon, and the solar system, as well identifying available resources at the south polar region for future *in-situ* resource utilization (ISRU).

Following mission completion, the crew will use the Ascent Element to return to the Gateway, where they will board Orion for transit back to Earth.

2.5 *Intermediate Missions Returning to the South Pole*

With Artemis 3 validating the system design for returning astronauts to the Lunar surface, immediate follow-on missions will begin setting up the necessary infrastructure to establish a permanent and sustainable presence at the Lunar south pole. These missions, which may be the next one or two missions, will land near Artemis 3 in order to make use of the resources and systems resident in the initial lander. These missions will carry four crew to the Lunar surface, following staging and integration of its elements at the Gateway.

One advantage compared to Artemis 3 will be the availability of pre-deployed assets now present on the Lunar surface from the CLPS missions. A pressurized Lunar rover could be placed on the Moon prior to crew arrival to support EVAs and improve overall mobility in the rugged terrain near Shackleton Crater. The ability to access destinations farther from the mission's landing site enables sample collection, measurement, and imaging of regions of the Lunar surface and subsurface that have never been explored.

On these missions to the surface astronauts will perform invaluable science, which aids in the understanding on how the Earth and Moon were formed. Example objectives include collection of Lunar regolith, rocks, and potentially a water ice sample. Investigation along with robotic partners of small craters, permanently shadowed regions (PSR), lava tubes, and tunnels will be performed. Lava tubes and tunnels may have potential as natural infrastructure for providing radiation sheltering.

2.6 *Full-Scale Lunar Architecture*

The remaining missions will be tasked with providing NASA global access across the Moon for sortie missions, alternating with returns to the South Pole. Solving global access leads to a robust, reusable lander design for long-term Lunar exploration.

At the equator, temperatures vary from 250°F to -208°F [3], making spacecraft design challenging. The Lunar poles are colder, but do not see the same temperature extremes as on the equator. When accounting for global access to the Lunar surface, vehicles must either account for up to a 90-degree plane change in the propellant budgets and/or timelines, or the Gateway must use the capabilities of the PPE to move to another high orbit better suited to global access sorties.

For missions returning to the south pole the deployment of a habitat prior to crew arrival is an important component of a sustainable Lunar architecture. The habitat will house equipment, science payloads, and consumables for supporting long-duration surface missions, as well as providing shelter and life support for future missions.

As discussed earlier, robotic missions could be used to pre-deploy assets that aid in the human exploration by generating consumables prior to the astronaut's arrival. This includes water and oxygen extracted from the Lunar regolith to breathe and drink or use as propellant. Pre-deployed power stations can collect, store, and beam power to landers or rovers, aiding in exploration through the Lunar night.

2.7 Robotic Exploration on the Lunar Surface

When it comes to humans on Moon, every minute is a precious commodity. To make the most of crew surface time, orbital and surface robotic explorers will act as pathfinders and scout areas with the highest potential return.

Polar landers and rovers will make the first direct measurements of polar volatiles. Their paths will be guided by data from orbital assets such as some of the satellites deployed during Artemis 1, and new orbiting spacecraft. The surface samples analyzed will characterize the lateral and vertical distribution, chemical composition, and overall physical state of the Lunar ice in this region. Future ISRU designs will be optimized to operate for these conditions.

Outside the poles, robotic rovers and landers can investigate scientifically valuable terrains not explored during the Apollo era. Discovery in these areas can enhance understanding on the early evolution of the Solar System and ultimately life on Earth.

Humans will augment these robotic discoveries, performing important heavy lifting operations that require real-time problem solving and dexterity that is not feasible with small robotic technology. As the Artemis roadmap progresses, the build-up of surface assets and infrastructures will grow (see Section 3.2) and pave a path for humans to Mars (see Section 4.2).

3. A Concept for Achieving Human Landing Missions on the Moon's Surface

With an emphasis on sustainability and safety, a multi-element HLS architecture leveraging existing systems can achieve NASA's bold timeline of transporting the first woman and next man to the Lunar surface, then leading to follow-on missions as envisioned in Figure 6.

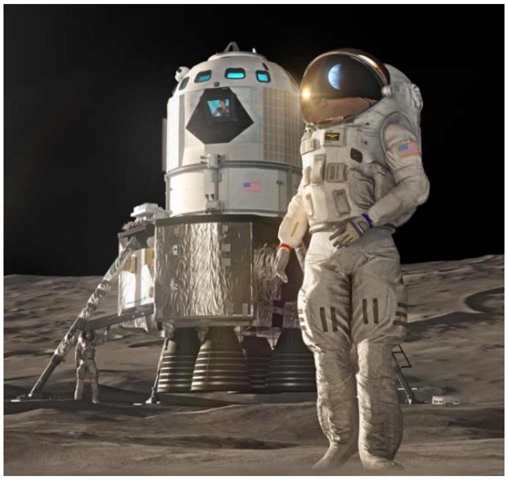

Figure 6. An artistic rendition of the next human Lunar lander concept.

3.1 Lunar Lander Overview

The key attributes of two of the stages of the architecture are outlined in Figure 7 and Figure 8.

The multi-element HLS is an aggregation and evolution of existing systems and capabilities. The Ascent Element crew pressure vessel is based on the Orion design methods but 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 Orion systems. This degree of commonality supports safety while leveraging existing deep space human rated systems in the most cost-effective way possible. The Descent Element builds off the autonomous guidance, navigation, and precision landing capabilities derived from LM's flight qualified deep space robotic exploration systems. By leveraging existing investments, NASA can send humans to the Lunar surface safely and affordably by 2024.

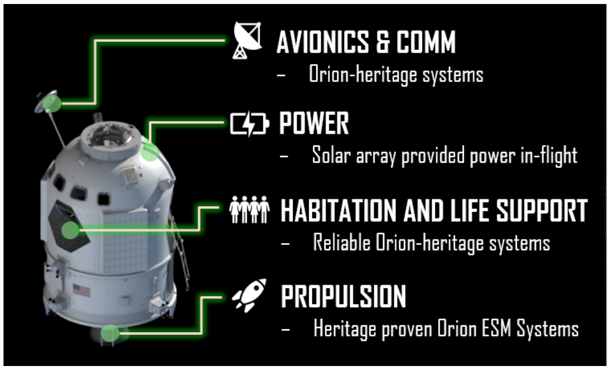

Figure 7. Ascent Element capabilities.

Figure 8. Descent Element capabilities.

3.2 Surface Infrastructure

The key to sustainable deep space exploration is transitioning from a "pack-in, pack-out" approach where astronauts must survive entirely on resources from Earth to "living off the land." The Artemis missions offer opportunities to deploy and demonstrate capabilities needed for self-sustaining deep space operations on and around the Moon.

Beginning with Artemis 3, HLS elements can be recycled to perform secondary missions after their primary objectives are complete. For example, once crew depart on the Ascent Element, the Descent Element can be repurposed as a service station, providing the following capabilities to future exploration missions:

- **Payload Support:** Host and deploy secondary payloads and scientific instruments
- **Power Generation:** Recharge surface assets and enable surface assets to survive the Lunar night
- **Surface Navigation:** Serve as a beacon for Lunar surface positioning
- **Communications Relay:** Amplify and transmit signals from the surface to the Gateway and onto Earth
- **Surface Refueling:** Provide storage for propellant generated from ISRU activities

The Descent Element is also capable of autonomously deploying assets to the Lunar surface in advance of crewed Artemis Missions. With an emphasis on affordability through commonality, a similar 3-bay pressure vessel used for the Gateway habitat can be deployed to the Lunar surface as a habitation module, as seen in Figure 8.

As the Artemis campaign progresses, core infrastructure on the Lunar surface will mature and expand. These capabilities can be leveraged by commercial and international partners, lowering the barriers of entry and transforming the Artemis landing sites to a place where sustained technological and economic development can take root.

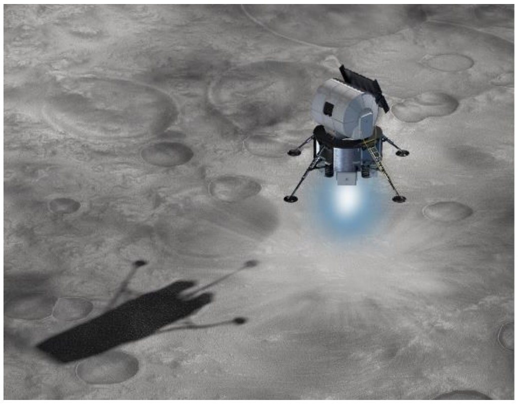

Figure 9. The Descent Module can pre-deploy a habitation module to the Lunar surface, extending the duration of crewed missions and enhancing exploration capabilities in preparation for Mars.

4. Moon to Mars: Preparing for Humankind's Next Giant Leap

The build-up and evolution of a Lunar exploration campaign at the Gateway paves the way for analogous Martian exploration operations via Mars Base Camp [4] (MBC), and lays the critical foundation for an innovative, sustainable, long-term program of exploration and eventual economic development. As current policy directives challenge the community to return humans to the Moon and on to Mars, Lunar exploration must proceed with Martian design requirements in mind. A Lunar exploration campaign with an eye towards Mars should therefore seek to accomplish three important objectives:

1. Develop and refine feed-forward platforms and skills to use at Mars
2. Generate data and critical hands-on experience working in deep space to decrease cost, protect safety, and improve performance at Mars
3. Lay the early foundations for a robust, water-based cislunar ecosystem that enables sustainable long-term deep space exploration

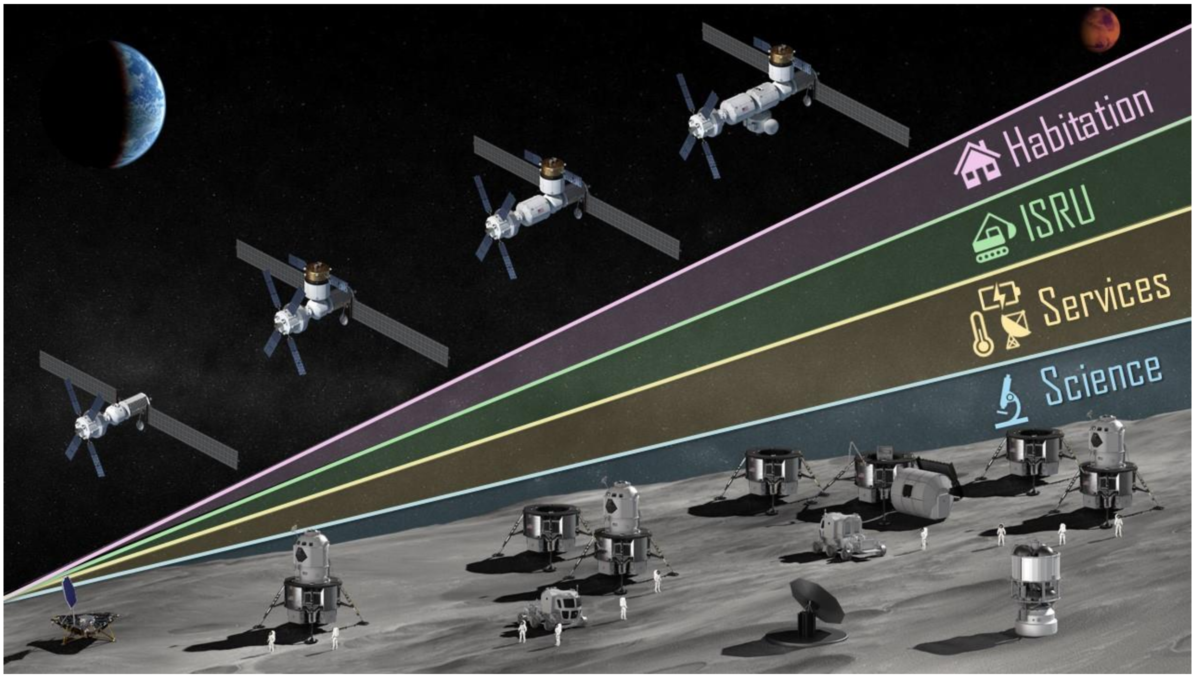

Figure 10. This graphic shows both the Gateway and Lunar surface build-up of capabilities.

4.1 Mature Platforms and Skills for Mars

The Lunar exploration campaign cannot offer point solutions for the Moon alone. Making elements of orbital and surface exploration forward-compatible reduces the cost, complexity, and development timeline of future Martian missions. It also provides opportunities to demonstrate and refine activities, platforms, and skills necessary to successfully orchestrate long-distance Martian missions in the relative safety of our own backyard.

There are notable differences in the Lunar and Martian environments, including that the Moon lacks an atmosphere, has roughly one-half Mars gravity, and its regolith is substantially clingier and more abrasive. Even with these differences, however, the majority of human Lunar lander activities executed from the Gateway are directly applicable to operating the Mars Ascent/Descent Vehicle (MADV) from the orbiting MBC vehicle. Chief among these activities are terminal descent navigation, guidance, and propulsion; surface EVA and operations; and ascent, rendezvous, and docking. An evolution of Lunar landers from an early two-stage version to progressively larger single-stage versions could help refine the architecture for the MADV platform and generate critical experience using key MADV systems like long duration cryogenic propellant storage.

4.2 Gain Experience Living and Working in the Deep Space Environment

A permanent Gateway in Lunar orbit serves as a proving ground for living and working in the unique and unfamiliar environment of deep space. The challenges faced in deep space are fundamentally different from what humans have experienced in LEO. Crew stationed in NRHO would be exposed to greater radiation levels than aboard the ISS, requiring them to build physical and procedural radiation countermeasures into their day-to-day life. At such a distance from Earth, crews experience increased logistical, operational, and psychological isolation not replicable in LEO. Crews will necessarily adopt the mindset of self-reliance that is so critical to deep space flight, while still being only several days away from rescue or resupply should anything go wrong.

As the cadence of robotic surface exploration missions increases, crew members at the Gateway will gain critical experience with teleoperations, preparing future MBC crewmembers for a long-term tele-operated Martian surface exploration campaign beyond the initial human landing. In addition to preparing crew for Mars, a strategy that incorporates robotic teleoperation and autonomy at scale is a great way to economically and effectively accomplish a campaign of in-situ surface exploration. A constant telerobotic presence, the resilience of robotic vehicles to Lunar night and permanently shadowed polar regions, their ability to operate autonomously for long periods of time, and the opportunity for real-time control without the risk to human lives combine to dramatically increase our knowledge of regions of scientific and economic interest, accelerate the identification of permanent settlement locations, and expand commercial activity beyond human exploration efforts.

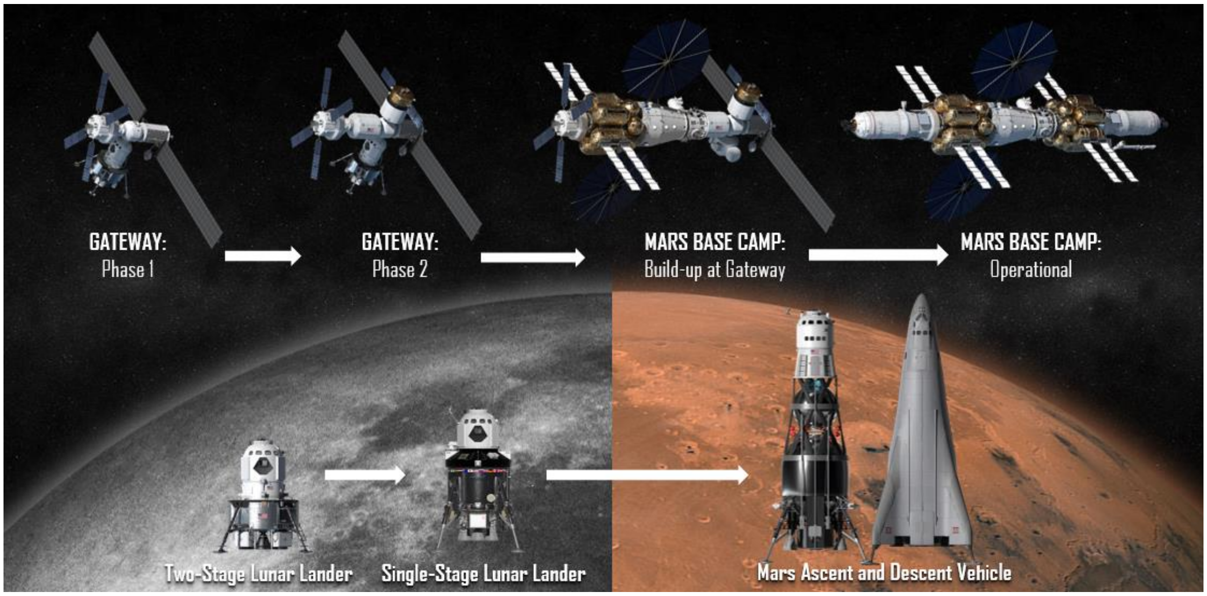

Figure 11. The designs and investments made in the Gateway and Lunar Lander are re-used and extended for Martian orbiting platforms and landers.

4.3 Key Mars Vehicle Systems are Demonstrated by Lunar Vehicles

All the systems needed for crewed Mars exploration vehicles will be demonstrated first on Lunar vehicles. Mars Base Camp requires both cryogenic propulsion systems for the Mars transit vehicle and the lander, and high power solar electric systems to deliver large cargo to Mars. The PPE is demonstration of the lower power version of the Mars solar electric propulsion system. It is expected that Lunar descent elements will use cryogenic propulsion. The Gateway habitat elements are prototypes for the Mars transit vehicle habitats and surface habitats. The Lunar lander Ascent Element cabin, including both habitation and crew command and control, is a prototype for Mars lander cabins. While the scientific questions to be answered are different at the Moon and Mars, the types of operations required at the Moon including sample return, telerobotics, field geology, and the study of human biology in deep space will be very similar for Mars. Large solar arrays, deep-space navigation and communication, autonomous operation, and surface infrastructure technology are required for both the Moon and Mars. The human experience at the Moon will begin to prepare crews for the journeys to Mars. Team psychology, radiation protection, microgravity exposure, and food production have already been explored on the International Space Station and will be exercised more at the Moon. Surface missions will increase the dangers, requiring a higher level of self-reliance, in-situ problem solving, and even a higher level of emergency medical training.

4.4 Lay the Foundations for a Sustainable, Robust Deep Space Ecosystem

For a space strategy to truly achieve long-term sustainability, it must foster economic activity that will remain self-sustaining after initial government exploration missions have concluded. Beyond its utility for returning to the Moon and sending the first humans to Mars, the presence of permanent orbital infrastructure, and eventually surface infrastructure, is a key enabler for a long-term exploration program that supports a more optimistic and expansive vision of humankind's future in space. A reliable location, first in orbit, and then on the surface as well, for life support, logistics, communication, teleoperation, resupply, and refuelling, enable sustainable Lunar activity. By reducing the cost and risk of missions to the Moon, permanent orbital and surface infrastructure encourage further exploration; attracts customers; encourages investment; catalyzes and sustains economic activity; promotes cooperative and complimentary international missions; and ultimately lays the foundation for a robust cislunar ecosystem that can sustain itself long after the last Artemis mission.

Permanent logistics nodes also serve the critical purpose of anchoring a nascent water economy. Just as all economic activity on Earth relies on fuel for energy and transportation, propellant will remain essential to every activity humankind undertakes in space, whether for purposes of sovereign exploration, commercial development, or even those as mundane as orbit maintenance. Liquid oxygen and liquid hydrogen remain the ideal propellants for their high performance and the presence of water on the Lunar surface and around the inner solar system [5]. The advancement of water as the commodity of choice for human exploration is arguably the most critical factor in establishing a commercially self-sustaining space economy.

The advantages of producing cryogenic propellants from water in space make a compelling business case and one central to the sustainability of space exploration. Until per-kilogram launch costs are reduced by an order of magnitude or more, refuelling empty spacecraft on orbit remains more cost-effective than launching fully-fuelled vehicles from Earth. As evidence of water's economic potential, several ventures have emerged in recent years targeting one or more segments of the space resources value chain. However, the paucity of customers and length of time required to mature investments to the point of profitability compared to more familiar terrestrial industries has discouraged investors, who with a few exceptions have largely adopted a strategy of waiting for another actor to prove out the risk and reward of a space resources venture. An initial customer who can provide the early demand necessary to catalyze this nascent industry, therefore, is required for said industry to emerge. In purchasing large quantities of water for its own exploration programs, a reliable government customer fulfils this role by demonstrating to private investors the technological and economic feasibility of in-space refuelling. In this way, this customer creates a stable economic framework in which further investment and development can occur with confidence.

Given the right initial conditions, it is expected that a water economy will develop with a competitive landscape of many suppliers supporting a wide variety of government, commercial, and international partners. The substantial economic benefits that would follow such a declaration help guarantee the formation of a robust, sustainable, and innovative in-space economy that expands humanity's sphere of influence beyond LEO and accelerates our path to Mars.

5. Conclusion

Even before Neil Armstrong and Buzz Aldrin first set foot on the Moon, humans were dreaming of the next leap to Mars. As a species, we have a natural born curiosity that compels us to extend our reach beyond our grasp. Each success is not seen as a finish line, but a stepping stone towards the future. When humans land on the Moon in 2024, they will set foot where no human has been before: the south pole. Applying lessons learned from the past will allow them to plant more than a single flag, gradually building a sustainable infrastructure. Only three days from home, astronauts can take reasonable risks, accelerating the pace of progress. Leveraging past investments in technology such as Orion allows this progress to march forward affordably, allowing astronauts to do more for less. As such, the power of the past is the legacy it leaves for the future, and from this legacy we can transform the horizon goal of Mars into a reality.

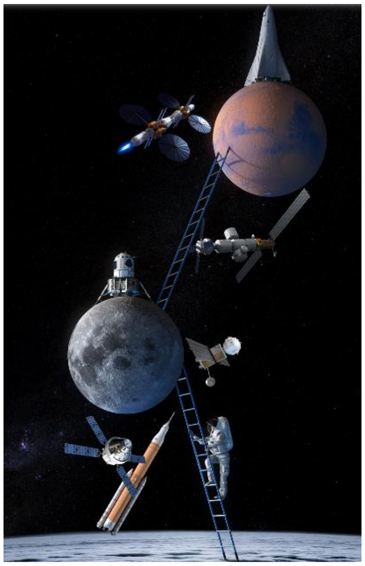

Figure 12. Deep space human spaceflight from the Moon to Mars.

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