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SLS, the Gateway, and a Lunar Outpost in the Early 2030s

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A human mission to Mars has long been an exploration goal of the United States and the international community, with a more recent focus on humans returning to the moon. To achieve these goals, NASA is developing the Space Launch System (SLS) and the Orion crew capsule as key elements in the architecture for missions to the moon and Mars. However, these aggressive goals are complicated by the need to optimize the use of government resources during a period when budgets are challenged. This paper discusses potential near-term missions that leverage Orion and SLS, as well as the Lunar Orbital Platform – Gateway, in order to establish an outpost on the lunar surface, as part of the overall campaign to eventually reach Mars. This campaign of lunar surface missions will create an outpost that can then be resupplied by commercial cargo and crew providers, while SLS and Orion continue to deliver the large components needed at the Gateway to test Mars exploration systems, finally culminating in a crewed Mars mission.

I. Introduction

NASA is currently working towards the goal of landing humans on the surface of Mars and returning them safely, leading to the eventual establishment of a permanent human-tended outpost on the surface of Mars [1]. They are pursuing this goal using an approach that has been dubbed the "Evolvable Mars Campaign" (EMC) [2,3].

A cornerstone of the Journey to Mars is the phased approach for exploration. As shown in Figure 1, the initial portion of the Journey to Mars has already begun. Studies are being carried out in low Earth orbit (LEO) at the International Space Station (ISS), including research into the effects of long-term exposure zero gravity environments on the human body and the efforts needed to mitigate any deleterious aspects of that exposure. Additionally, long-term Environmental Control and Life Support Systems (ECLSS) and other necessary technologies are being developed and demonstrated in the relative safety of LEO.

The next phase of the EMC begins in 2020 with the launch of the first Space Launch System (SLS) and Orion flight to the lunar vicinity. Future missions will continue to build up habitable infrastructure in cislunar space and test the embedded systems for reliability in that environment. Crewed missions to that habitat will exercise those systems under realistic conditions that cannot be simulated either on Earth or in LEO in preparation for future missions to Mars.

The cislunar space exploration phase further proves out the efficacy of the spacecraft systems in progressively longer duration stays, culminating in a "Mars Shakedown Cruise". Additionally, there has also been a renewed call to return astronauts to the surface of the moon, both in the U.S. [4] and from international partners [5]. Human missions to the lunar surface would utilize the cislunar habitat as a staging point. These missions would serve as early learning experiences for eventual Mars surface missions. Telerobotic exploration of the moon will provide experience in those operations for future Mars missions.

The Mars exploration phase begins with the initial human forays into the Martian system. The initial mission will be a human orbital mission with attendant systems to allow for direct human exploration of the Martian moons, Phobos and Deimos, as well as the telerobotic exploration of the Martian surface, utilizing either prepositioned robotic assets or assets that are brought along with the crew. Future missions to the Martian system will involve the buildup of a permanent infrastructure on the Martian surface to enable long-term human exploration of the planet.

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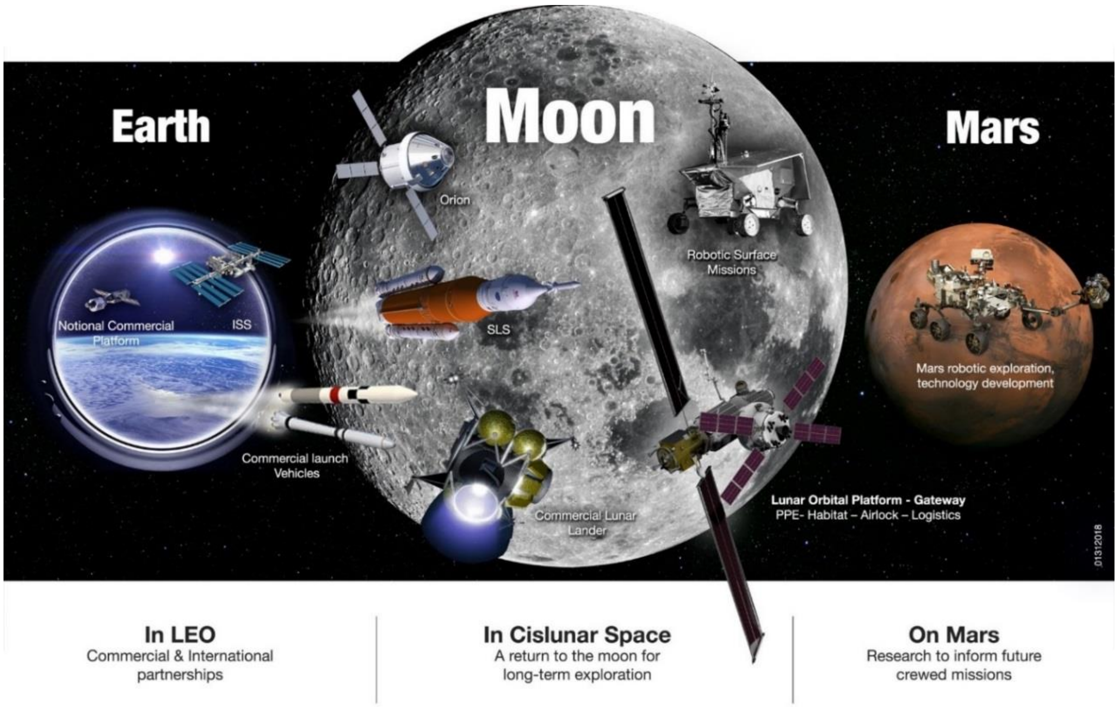

Figure 1. Incremental Approach to Mars Exploration. Source: NASA

II. Basic Components

To accomplish the Journey to Mars, six major system elements need to be developed. Those elements are shown in Figure 2. The six elements break into three groups: Earth's gravity well, deep space, and Mars' gravity well.

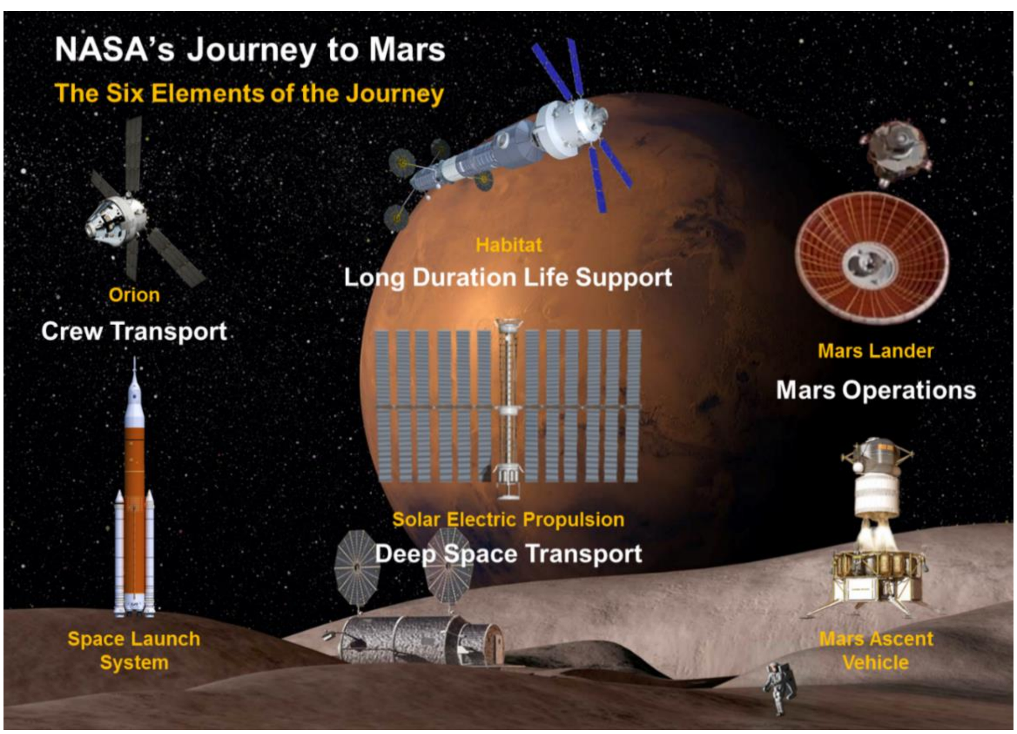

Figure 2. Six Elements for Journey to Mars. Source: Aerojet/Boeing/Lockheed/Innovation Systems (Orbital ATK)

A. Earth's Gravity Well – SLS and Orion

The two elements currently in development and nearing completion are SLS and Orion. The first uncrewed mission of the two elements is currently scheduled to launch in mid-2020 for a trip around the moon [6]. The more capable SLS Block 1B vehicle with the Exploration Upper Stage, shown in Figure 3, will first fly in 2024 for EM-3.

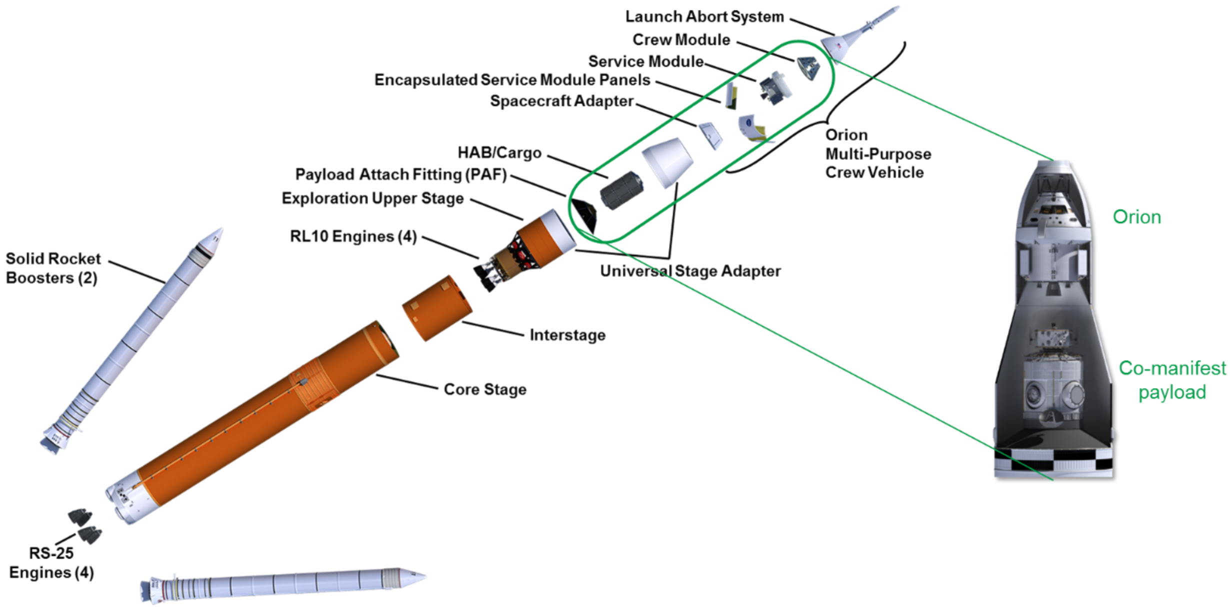

Figure 3. Expanded View and Cutaway of SLS Block 1B, Crew Configuration: Source: NASA and Boeing

The Orion crew capsule is currently capable of up to 21 days in space with a crew of four while having a heat shield capable of handling the reentry to earth from lunar velocities [7]. A fully loaded, lunar mission capable Orion with a docking ring is assumed to have a mass of 27.2 mT [8,9].

Along with delivering Orion to cislunar destinations, SLS Block 1B has additional payload capability. This capability is utilized by delivering co-manifest payload (co-manifest with Orion). This co-manifest payload is carried inside the payload attachment hardware. Figure 3 shows an expanded view of SLS, as well as a cutaway of the top of SLS, including Orion, and an example of a co-manifest payload inside the universal stage adapter. Co-manifesting payload with Orion provides new flexibility in achieving human exploration, operations, and science objectives on any given mission.

The launch rate of SLS is assumed to be one per year starting in 2020, increasing to two launches per year beginning in 2031, with a possible surge to five launches every two years beginning in 2036.

B. Deep Space – Habitat and Propulsion

Following the development of SLS and Orion, the next pieces necessary for the Mars campaign are the Deep Space Habitat (DSH) and a deep space propulsion system. The habitat and propulsion system are often combined into the Deep Space Transport (DST).

One likely propulsion method for the DST is solar electric propulsion (SEP). SEP turns solar power into thrust by using solar arrays to generate electricity, which is then used to power Hall-effect thrusters. SEP typically has very low thrust – in the tens of Newtons – coupled with a very high specific impulse (Isp), which is a measure of efficiency, of around 3,000 sec. Because of the low thrust, SEP takes a long time to deliver payload, but the high Isp means it can do so for relatively small amounts of propellant. This is effective for delivering cargo, where long mission times are acceptable in exchange for less propellant.

For delivering crew, SEP alone is not sufficient – the very low thrust results in very long mission times. A hybrid propulsion system has been proposed, which combines SEP with traditional hypergolic propulsion [10,11]. The hypergolic propulsion would be used for orbit departure and insertion burns, where higher thrusts are more advantageous, and SEP would be used to shorten the time between destinations.

C. Mars Gravity Well – Lander and Ascent Vehicle

Eventually, the elements necessary to descend to the surface of Mars and return to orbit – a lander and an ascent vehicle – will need development. Since a Mars landing is further in the future, the funding and development of these elements can be arranged after the other elements have been developed and are in use.

While some elements of the lander and Mars ascent vehicle (MAV) could be longer term, such as a liquid oxygen (LOX)/methane engine and aeroshell-based deceleration, other elements could be developed and tested as part of a lunar landing campaign.

III. SLS Block 1B Capability

A. Modeling Methods

The trajectories for the SLS Block 1B configurations are modeled in the present work using the Program to Optimize Simulated Trajectories, or POST [12]. The input model was developed internally by Innovation Systems (Orbital ATK) using NASA ground rules and assumptions. Payload for this study is defined as mass above the cargo payload adapter (CPA). The trajectory is modeled from launch to an initial parking orbit, then on to a characteristic energy (C_3), representative of leaving for a beyond Earth orbit (BEO) destination. POST optimizes the payload delivered to the defined C_3.

The in-space modeling is done in Copernicus [13]. Models are created to calculate delta velocity (ΔV) for the different mission segments, including LEO to lunar halo orbit, lunar halo orbit to low lunar orbit, and low lunar orbit to the lunar surface. The model results are used to determine the propellant required for the various mission segments, either directly from the model (finite burns) or by using Tsiolkovsky's equation (ΔV results).

B. In Space Modeling

In order to model SLS capability, we first model the departure from LEO to arrival at the Gateway. This study assumed that the Gateway is located in near rectilinear halo orbit (NRHO) [14]. While NRHOs appear to be polar elliptical orbits, they are actually halo orbits with large amplitudes around the Lagrange points (EML1 and EML2) [15]. They remain relatively fixed in the Earth-moon frame, meaning that they have a constant line-of-sight to Earth.

An example of a Copernicus model output is shown in Figure 4. The model starts at a 100 nmi circular LEO. It then simulates the Earth departure burn, shown in terms of both ΔV and C_3. After a coast, the model calculates the ΔV for a lunar flyby, a second coast period, and a final lunar orbit insertion burn. The calculated ΔV, with some added margin, are used to calculate both the performance of SLS from LEO through the Earth departure burn, and the propellant required by the payload to reach the Gateway in NRHO.

Another Copernicus model calculates the ΔV required to go from NRHO down to low lunar orbit (LLO). The ΔV required from LLO to a lunar landing is also modeled. The values calculated by the models are compared to published sources and papers and are found to be generally in agreement. These ΔV calculations ensure that the lunar lander has sufficient capability to get to the lunar surface from the Gateway.

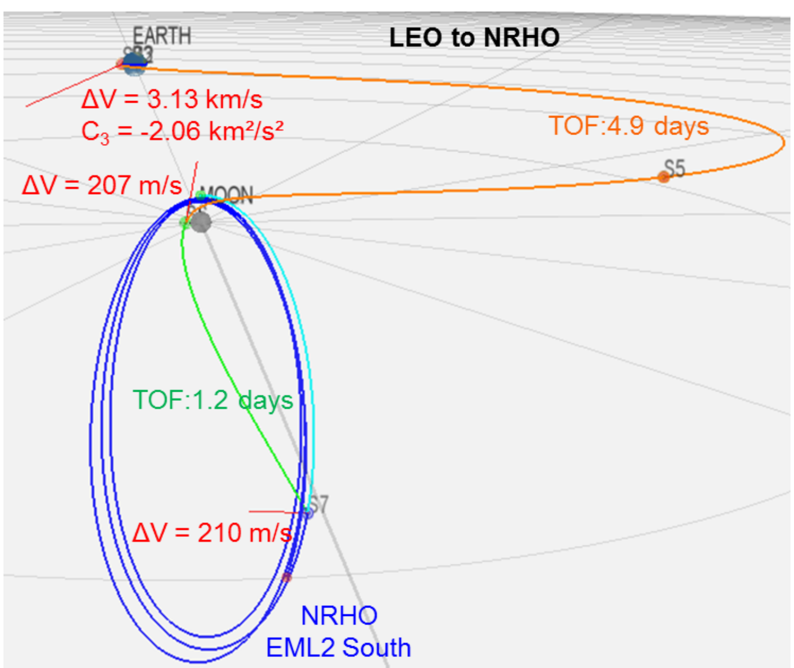

Figure 4. Example of LEO to NRHO Trajectory

C. SLS Block 1B Crew

SLS Block 1B in the crew configuration – with Orion and co-manifest payload as described above – are modeled from launch at Kennedy Space Center (KSC) to an initial orbit of 100 x 100 nmi. The payload remains in orbit for two revolutions, after which the Exploration Upper Stage (EUS) engines reignite, providing the thrust to deliver the payload to a BEO destination. For this study, Orion's destination is the Gateway in NRHO [15]. SLS is modeled to deliver the payload to C_3 = -2.0 km²/s², sufficient energy for the payload to arrive in the vicinity of the moon. This study assumes that the payload is responsible for insertion into the NRHO. This could be done either by Orion's service module or by a propulsion module carried with the co-manifest payload.

EUS is currently not designed to provide long-duration in-space propulsion capability, due to cryogenic storage limitations. This effort therefore assumes that EUS provides the trans-lunar injection (TLI) burn, but is not available to insert into NRHO.

Given these assumptions, the POST model shows that SLS Block 1B could deliver 37 mT of payload to NRHO. Of this payload, 27.2 mT is assumed to be Orion, leaving 9.8 mT for co-manifest payload. It is assumed that Orion would provide the ΔV to insert from TLI into the NRHO.

D. SLS Block 1B Cargo

The model of SLS Block 1B in the cargo configuration simulation is similar to the crew configuration approach. The biggest difference is in the front-end hardware – fairing and payload adapter are present rather than Orion and Launch Abort System (LAS). This study delivers payload to TLI (C_3 = -2.0 km²/s²). Given these assumptions, POST estimates that SLS could deliver 41 mT of cargo-only payload to TLI. As with crew, the payload is assumed to be responsible for its own lunar orbit insertion burns.

E. SLS Block 2B

At some point, the supply of steel booster cases will be exhausted, and the booster cases will transition to composite material. This will decrease the inert mass of the boosters, resulting in an increase in payload. Additionally, modest core stage and EUS mass savings are also assumed for the 2B configuration, combining for an additional 6 mT of payload to TLI.

IV. Establish the Gateway

The proving ground missions begin with EM-1, an uncrewed test of SLS Block 1 and Orion, slated for mid-2020 [6]. This mission tests the capabilities of SLS to deliver payloads to LEO, and Orion to safely deliver astronauts to lunar distant retrograde orbit (LDRO) and return them safely.

The following mission, EM-2, is the first crewed mission for SLS and Orion and is targeted for 2021. It is a repeat of EM-1, launched on Block 1, this time with crew on-board. This mission is the first crewed return to the lunar vicinity since Apollo 17 in 1972.

In 2022, SLS Block 1 launches the Europa Clipper [16]. Launching the Clipper on SLS allows for a direct trajectory, rather than multiple planetary flybys, thus reducing the flight time to arrive in the Jupiter system from around seven years to less than three years [17].

The construction of the Lunar Orbital Platform – Gateway (or simply the Gateway) begins in 2023, with the delivery of the power and propulsion element (PPE) to NRHO on a commercial launch vehicle [18]. Gateway is a modular space station located in NRHO, which will be used to test and verify the technologies and procedures for deep space crewed missions [19,20]. It serves as the gateway for lunar landing and deep space missions, as well as providing opportunities for international and commercial missions. After launch, the PPE inserts into orbit around the moon.

This study assumed that the Gateway is located in NRHO, but there are many potential lunar orbits that facilitate a sustained human presence near the moon. Several cislunar destinations have been considered, including LDRO, NRHO, and other halo orbits around Earth-Moon Lagrange points (EML1 and EML2) [15]. All of these destinations have advantages and are suitable for longer-duration missions to cislunar space.

The initial proving ground missions are summarized in Figure 5.

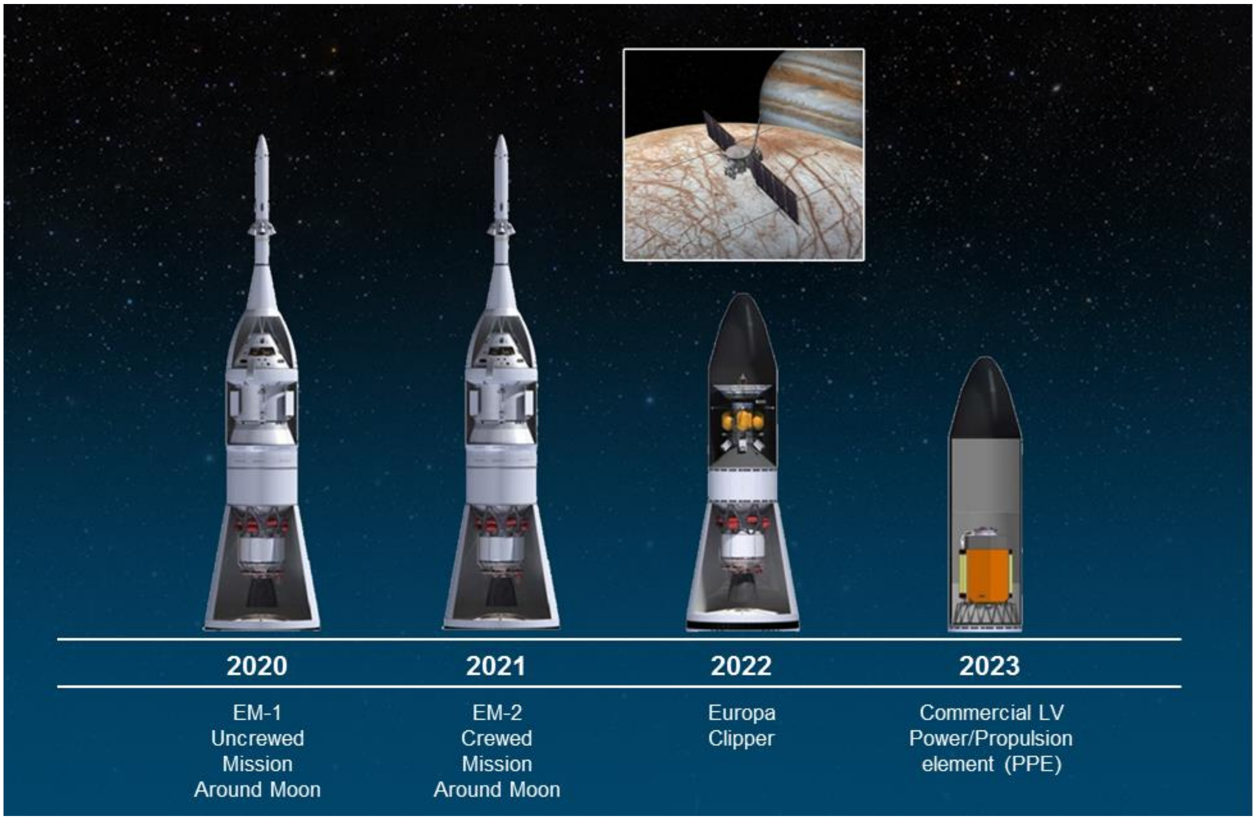

Figure 5. Initial Proving Ground Missions. SLS images courtesy Boeing Corporation and Innovation Systems (Orbital ATK).

The next phase of the proving ground mission – crewed missions to the Gateway – commences with EM-3 in 2024. EM-3 is the first mission of SLS Block 1B with the EUS. This mission, and those that follow, takes advantage of SLS Block 1B's co-manifest payload capability to deliver the Initial Cislunar Habitat (ICH) along with Orion. After the SLS has pushed them towards the moon, Orion docks with the ICH, and together they journey into cislunar space, where they rendezvous with the PPE launched previously.

The ICH provides extended living volume and supplies, extending the duration of the mission beyond Orion's capability. At the end of the mission, the ICH remains in cislunar space with the PPE, becoming the backbone of the Gateway, as shown in Figure 6.

The following missions – EM-4, -5, and -6 – are similar to EM-3, where SLS delivers Orion and co-manifest payload pieces to the now-growing cislunar platform, summarized in Figure 7. The delivered modules would likely include a node module and an airlock module. At this point, with the node module in place, there would also be opportunities for commercial cargo delivery to the Gateway [21].

Each successive mission increases the time that the crew spends at the platform. EM-3 is likely to be a relatively short 30-day stay, increasing to a 90-day stay on EM-6. This creates natural stepping stone proving ground missions, as astronauts learn to stay in deep space for longer periods. This tests vital ECLSS, supply, and communication systems that will be needed on the much longer missions to come.

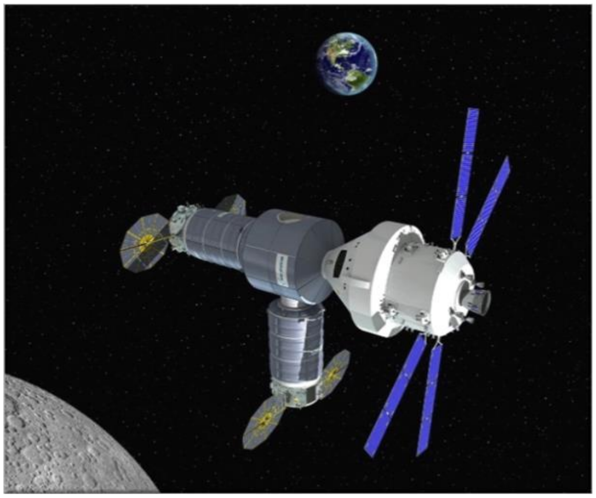

Figure 6. Notional Cislunar Habitat with Orion

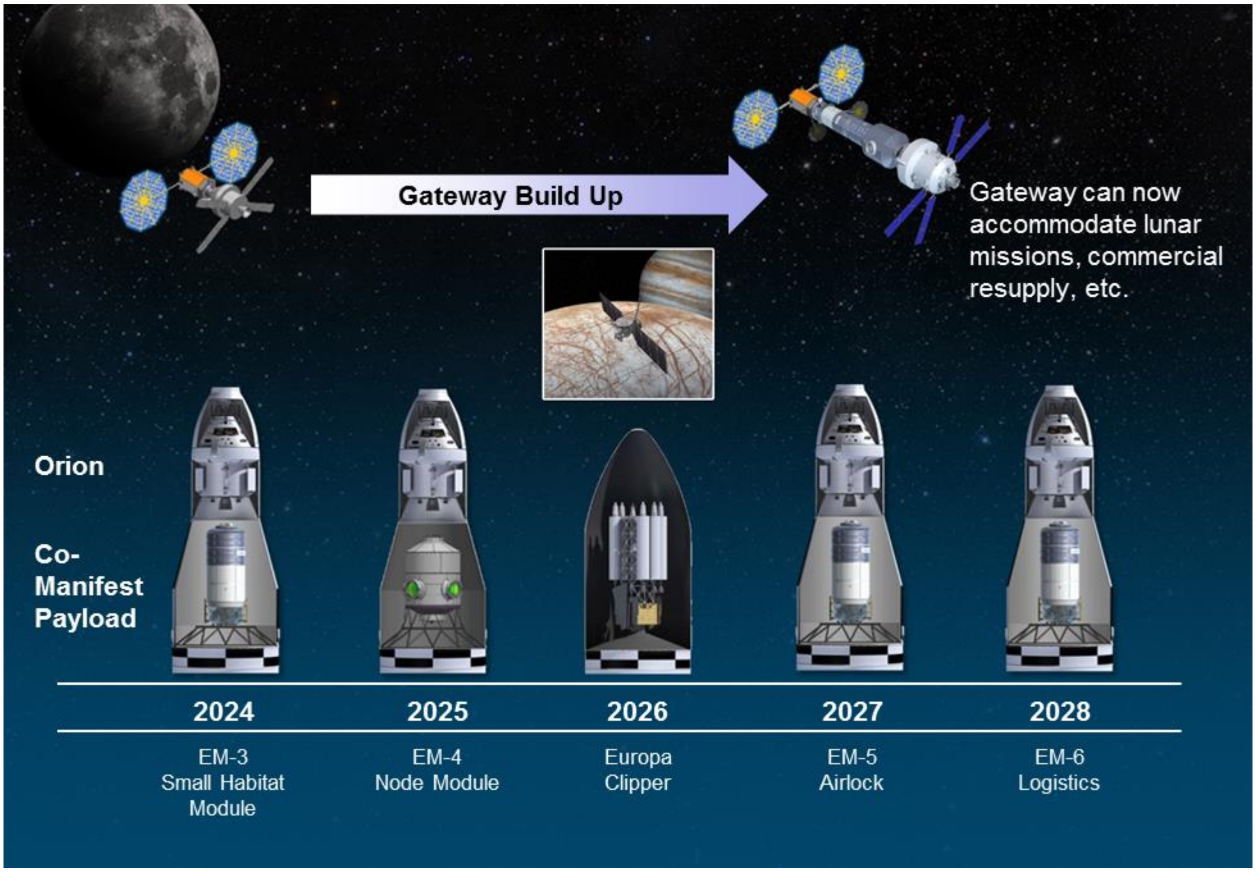

Figure 7. Initial Proving Ground Missions (cont). SLS images courtesy Boeing Corporation and Innovation Systems (Orbital ATK).

In addition to the expansion of the Gateway, a second mission to Europa launches in 2026. This mission would include a lander that would descend to the surface and take measurements of the ice [22]. As with the Clipper mission, launching the lander on SLS allows for shorter time of flight.

The first phase of the Mars campaign concludes with the Gateway fully established in cislunar space; commercial cargo deliveries have been enabled; and the capability of SLS and Orion have been validated, with eight launches of SLS and six Orion flights.

V. Validate Mars-Class Systems in Cislunar Space

The next step of the Mars campaign begins in 2029. The goal of this phase is to validate the systems needed for a Mars-class mission. This includes missions to the lunar surface to practice landings, habitation, and ascent, as well as a long-duration shakedown cruise.

There have been countless studies addressing returning humans to the surface of the moon – including lander designs, habitat designs, mission architectures, lunar economy ideas, and more. This study will not attempt to summarize all the ideas or address all the trades – we are presenting one possible lunar campaign, based on the available components and technologies.

A. Lunar Architecture Choices

To that end, we made some decisions up front about the lunar campaign architecture in order to limit the scope of the present study. These decisions were informed by earlier studies that looked at architecture decisions trees [23,24].

The first decision was to choose an outpost style architecture rather than a lunar sortie architecture. While the lunar sortie architecture allows for the crew to explore multiple locations around the moon, the outpost architecture allows for the gradual build-up of components to enable long-duration missions to the surface – with the goal of eventually having a permanently crewed outpost, similar to Antarctica. Adding robust surface mobility capability enables exploration over a wider area.

Second, to construct the outpost, we needed to decide on the role of the lander [23]: whether to use the lander as part of the construction or whether to offload the components from the lander. If the components are to be offloaded, then we needed to decide whether to use external offloading, such as a crane (passive), or whether to have the components use self-powered surface transportation capability (active). For this study we chose a combination of using the lander and using active component capability.

Next, we looked to limit the trade space of the lander, specifically, what to stage and when. Options include staging tanks from the descent module (DM) before landing, staging the ascent module (AM) at the surface, and having a single stage act as both DM and AM [25]. For this study we assumed the Apollo-style surface staged DM, where the DM stays on the surface while the astronauts ride back to the gateway in the AM. Other options are possible, but this option has the fewest unknowns, due to Apollo experience.

For lander propulsion, the options include hypergolic (nitrogen tetroxide and mono methyl hydrazine [NTO/MMH]), liquid oxygen and liquid methane (LOX/LCH4), and liquid oxygen and liquid hydrogen (LOX/LH2) [26]. LOX/LCH4 is most likely what will be used for the MAV, due to the hope of producing LOX and LCH4 in situ on Mars. However, LOX/LCH4 currently has the lowest technology readiness level (TRL) of the three choices. LOX/LH2 has the highest Isp, but LH2 is highly cryogenic, requiring significant effort to keep it from boiling off. NTO/MMH is highly toxic, but it is hypergolic – requiring no separate ignition system – and easily storable, and there is a long history of using NTO/MMH in space. For this study, we used NTO/MMH, since it has the highest system TRL. The landers can be built with existing technology, allowing technology development work necessary for Mars systems to proceed so that they can be ready when required.

Finally, for surface power, we chose the fission powered Kilopower concept [27] rather than solar arrays. While solar arrays have a higher TRL, Kilopower offers more power in a smaller volume. It is also a more reliable source of energy, since it is not dependent on being in a location with constant sunlight, of which there are very few on the lunar surface. Kilopower is also being advanced as the power source for Mars surface missions, so using it at the lunar outpost would allow for developing and testing the technology. Development is on-going, with live tests recently conducted in the Nevada desert [28].

B. Lunar Outpost Components

The build-up of a lunar outpost is similar to the build-up of the Gateway. Initial components will need to include the capabilities needed to sustain the crew on the lunar surface. The crew components would likely include the DM, AM, a basic capability habitat module, an advanced capability habitat module, an unpressurized rover, and a pressurized rover.

Robotic/uncrewed systems would also need to be part of a lunar outpost campaign. These components could include power and communication systems, a crane, transport rovers (similar to the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) [29]), mining rovers, and 3D printing rovers (to convert regolith into structures [30]). Eventually there would be a need for an electrolysis plant for converting lunar water into LOX and LH2, as well as a storage and refrigeration plant to store them for both crew needs and propellant.

C. Lunar Lander

The present work assumes the use of a lunar lander lately proposed by Boeing [31], Figure 8. The DM includes a habitat module as well as an airlock, making the distance to the surface shorter than either Apollo or Altair. The DM is powered by 12 Starliner-derived NTO/MMH engines. The AM docks to the top of the DM and is powered by four Starliner-derived NTO/MMH engines. The crew accommodations in the AM are designed for short-term transit to the Gateway.

The mass of the DM is estimated to be 43.5 mT total, with 32.5 mT of propellant. The mass of the AM is estimated to be 7.5 mT total with 4.5 mT of propellant [31].

A cargo variant of the DM would also be required. This variant would use the DM basic structure, tanks, and engines, and would carry cargo instead of the habitat and airlock. This

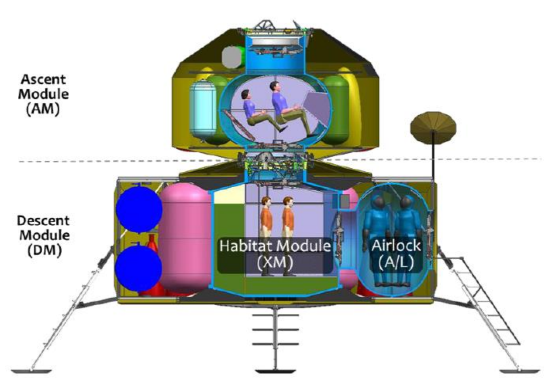

Figure 8. Boeing Lunar Lander Design [31]

study assumed that removing the airlock, habitat module and docking system would remove 3 mT of mass from the DM. Based on mission requirements, we calculated that the cargo DM would be capable of delivering 9.5 mT of cargo to the lunar surface.

D. Lunar Campaign

This lunar campaign is built on the assumption that the Gateway is up and running, and that SLS is available to launch twice per year beginning in 2031. A summary of the lunar campaign is shown in Figure 9 and Figure 10.

The first lunar outpost component is launched in 2029 on an SLS Block 1B cargo mission. The cargo variant of the lander delivers a power and communication module, consisting of two or three Kilopower units as well as a communication system to allow the outpost to communicate with the Gateway and Earth. An optical communication system would be the likely choice [32]. The lander also lands several small rovers, which could be tele-operated from either Earth or the Gateway. These rovers could include mining rovers to prospect for minerals and water, a bulldozer rover to flatten landing sites, or a 3D printing rover to build berms around future landing sites.

The SLS launch in 2030 is a crew mission to the Gateway, carrying supplies in a logistics module. The logistics module could remain with the Gateway as added habitable volume, or be filled with trash and discarded.

In 2031, a cargo SLS carries the crew DM to the Gateway. A crew SLS follows, with the AM carried as co-manifest payload along with Orion. The AM and DM mate up at the Gateway, and the crew boards and then descends to the lunar surface. The crew lives in the DM's habitat module while on the surface. They check out the power and communication systems delivered the year before. Then they take the AM back to the Gateway, where Orion is waiting to return them to Earth.

The mission in 2032 is again a cargo DM, launching on the cargo SLS. The cargo is a basic habitat module. The habitat module includes a transportation capability – something like ATHLETE – and it moves to its permanent location, controlled from either the Earth or the Gateway. The crew launch in 2028 is another mission to the Gateway with a logistics module.

Figure 9. Lunar Campaign Missions, Part 1. Source: Boeing [31] and Innovation Systems (Orbital ATK)

Crew again visits the lunar surface in 2033, again using two SLS launches to deliver the DM and AM using cargo and crew configurations, respectively. This crew connects the power and communication to the habitat, and checks out the function of the habitat. They also connect the habitat to the previous crew DM, taking advantage of the habitable volume.

In 2034, another cargo SLS and cargo DM delivers a more advanced habitat, perhaps an inflatable habitat module. This module connects to the existing habitat, creating the backbone of the lunar outpost. The 3D printing rovers work to bury the habitats in regolith, for protection from radiation and micrometeorites.

The crew mission in 2035 checks out the more advanced habitat module. After this mission, the outpost is operational. It is available for missions by international partners, as well as commercial resupply and commercial crew.

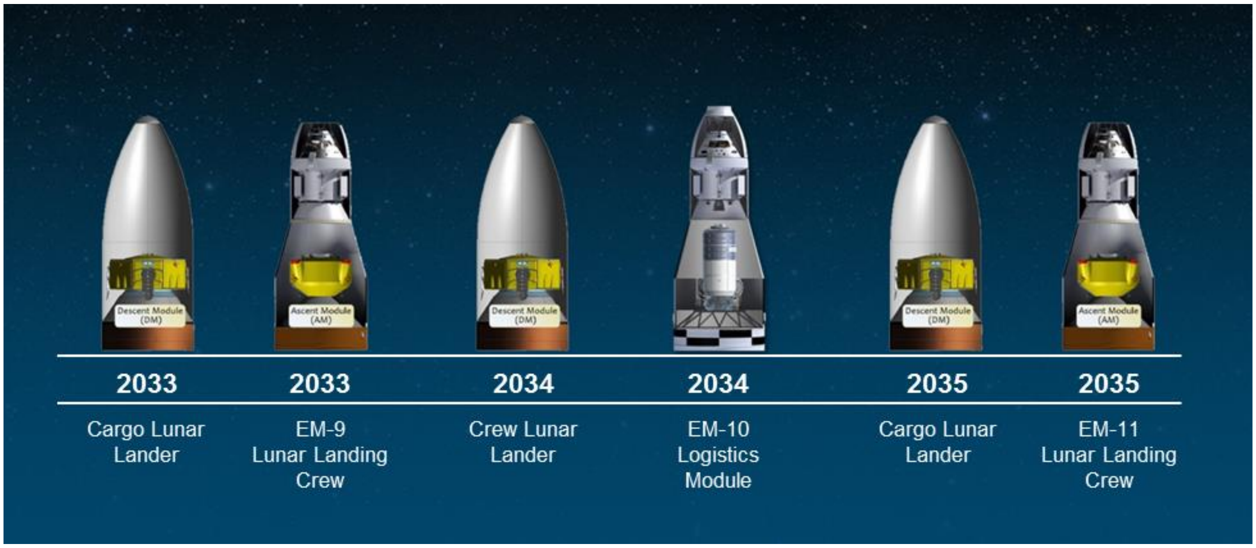

Figure 10. Lunar Campaign Missions, Part 2. Source: Boeing [31] and Innovation Systems (Orbital ATK)

E. Mars Shakedown Cruise

Beginning in 2036, the focus of SLS shifts to deep space missions, with a summary shown in Figure 11. In 2036, SLS launches the DST, the habitat and propulsion needed for long-term deep space missions. We assumed a point-of- departure design for a deep space habitat design as described by Simon et al. [33]. This habitat design assumes a crew of four, with a stowed diameter of 7.5 m, such that it fits within the current SLS 8.4 m fairing. The design features a vertical orientation, divided into two decks. It also features four docking hatches – one on the forward end, intended for Orion, and three radial hatches for logistics modules.

A second SLS launch in 2036 takes crew to the Gateway, where they checkout the DST. In 2037, a cargo launch takes fuel and logistics to load up the DST, after which a crew launch takes crew to the Gateway, where they board the DST for a shakedown cruise. Several ideas have been suggested for this initial shakedown cruise [34]. A mission away from the Earth's sphere of influence is a good choice for a shakedown cruise – far enough away to be interesting but not so far that it takes longer than about a year.

McGuire et al. proposed such a mission [34] – a roughly one-year mission to asteroid 2000 SG344. Asteroid 2000 SG 344 is a small Aten-class asteroid with an orbital period of 353 days, an estimated mass of 71 mT, and an estimated diameter of 37 m [35,36]. There are likely other suitable asteroids that would also be good candidates for this mission.

The mission to SG344 has a total round trip of about 400 days, including 30 days at the asteroid [34]. The DST uses its hypergolic propulsion to depart from lunar orbit, after which it utilizes its SEP throughout the remainder of the mission.

An advantage to delaying the DST delivery and shakedown cruise until after the lunar outpost campaign is that it allows more time for propulsion development, either chemical or solar electric, as well as time to incorporate lessons learned from the Gateway.

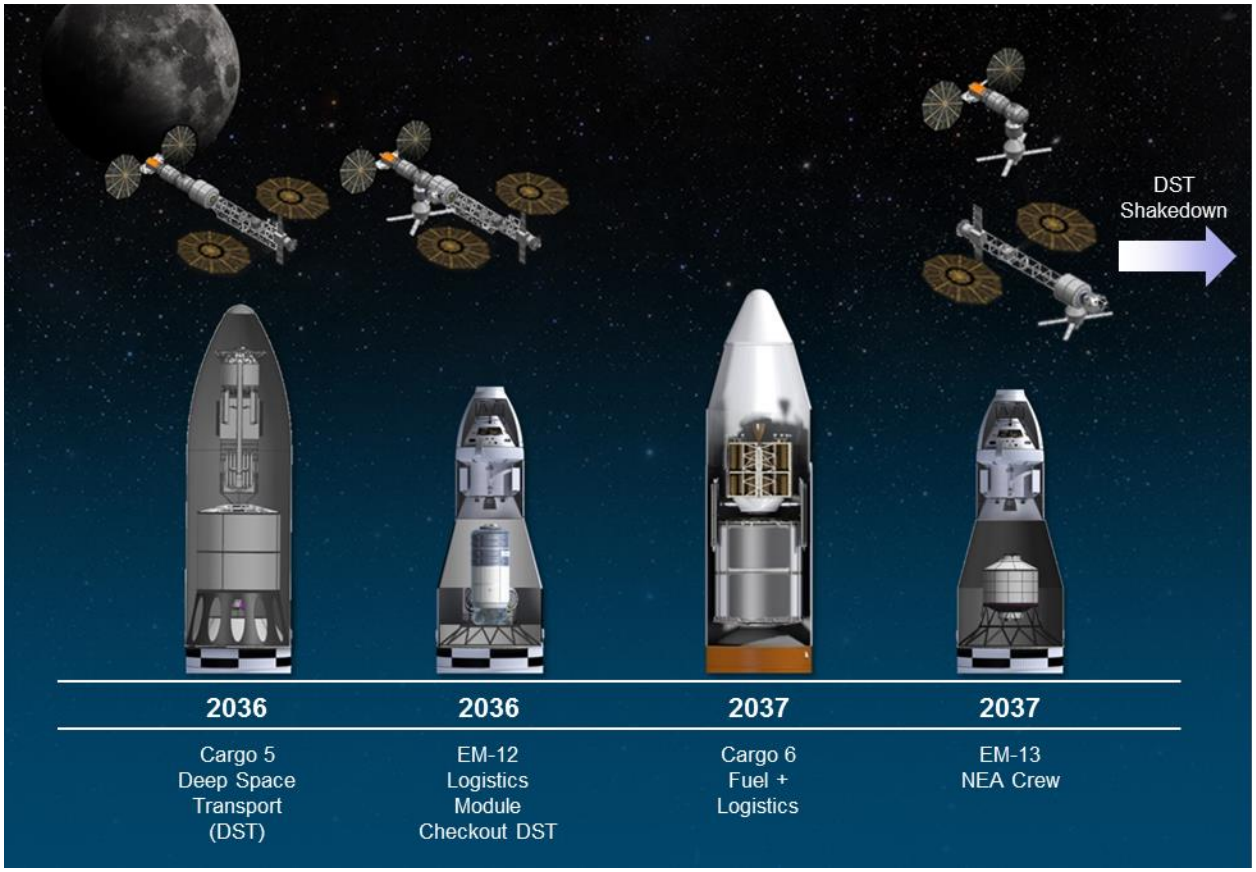

Figure 11. Proving Ground Missions. SLS images courtesy Boeing Corporation and Innovation Systems (Orbital ATK)

VI. Journey to Mars System

With an operating Gateway, an operating lunar outpost, and a successful shakedown cruise, the Mars campaign now moves into the Mars exploration phase, using the components and experience from the earlier phases to deliver crew to Mars. SLS delivers the necessary large components to the Gateway, where they aggregate and eventually depart for Mars. This campaign begins with a Mars orbit/Phobos rendezvous mission, departing in the 2041 Earth-Mars window, with the summary shown in Figure 12. A crewed Mars landing mission follows in the 2045 Earth-Mars window.

VII. Lunar Outpost Going Forward

The Mars campaign moves on, but the lunar outpost also continues to operate. With an SLS launch cadence of five every two years, there would be an SLS available to launch a large lunar outpost component every two years (with the other four launches dedicated to deep space components).

Additionally, commercial resupply and crew delivery opportunities are available after 2035. United Launch Alliance (ULA) is designing a lunar lander, Xeus, based on the Vulcan ACES upper stage [37]. Blue Origin is designing a cargo lunar lander, Blue Moon, which could be scaled up to deliver crew [38]. With an operational lunar outpost, commercial crew and resupply, from Earth or the Gateway, would keep the outpost viable and operating.

International partners, including the European Space Agency (ESA) [5], China [39], and Russia [40], have also expressed interest in building a lunar outpost. Allowing them to visit and work at this outpost would possibly bring additional components, supplies, and crew, furthering international cooperation and lunar science.

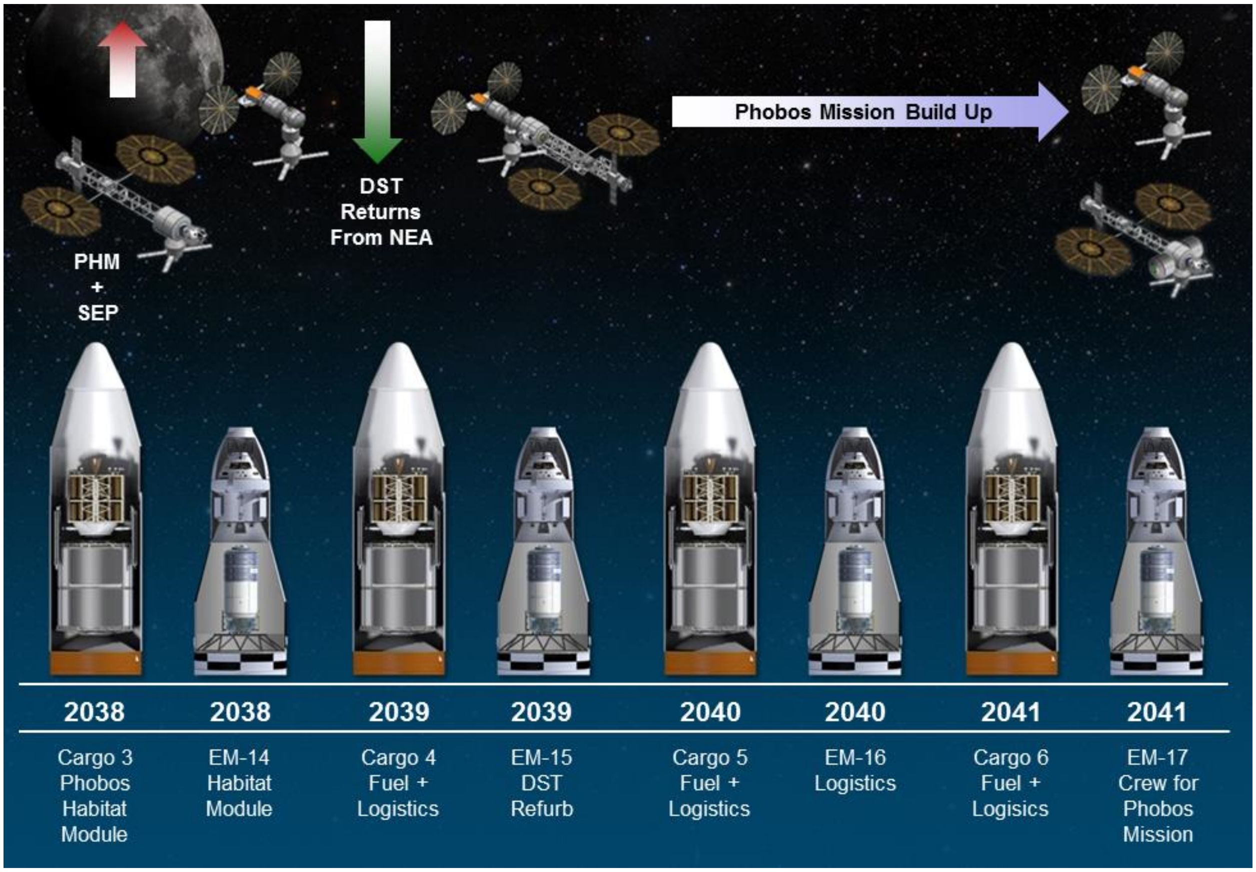

Figure 12. Phobos Missions. SLS images courtesy Boeing Corporation and Innovation Systems (Orbital ATK)

VIII. Why SLS and Orion? Why Not Exclusively Commercial?

Enabling commercial crew and cargo deliveries to the lunar outpost begs the question: why use SLS, Orion, and the Gateway? Why not use exclusively commercial launch vehicles and landers? The SLS and Orion system bring several advantages to the table that make the lunar outpost more likely to both happen in the first place, and then to thrive once it is established.

First, SLS can also take advantage of its large, 8.4-meter-diameter payload fairing. This is much larger than planned Evolved Expendable Launch Vehicle (EELV) fairing diameters and allows for a wider array of lander designs. This fairing volume allows large diameter components to be launched. An earlier study looked at the impact of launch vehicle fairing on architecture components and found that a smaller diameter fairing challenges many aspects [41]. Packaging payload components is more of a challenge. Smaller diameter landers must be taller, meaning both higher center-of-gravity (CG), leading to controllability challenges, as well as longer descents for crews from the lander to the surface.

Additionally, SLS enables heavier lunar landers and habitat modules to be delivered to the Gateway in one piece. Smaller launch vehicles would have to send the DM and its fuel separately, increasing the number of operations to be performed. The habitat modules would have to be sent up in multiple pieces, increasing the complexity of the system. Single piece launches are thus to be preferred.

The additional capability of SLS also allows the use of the higher TRL but lower efficiency and therefore more massive hypergolic propulsion. This allows the lander to be developed more quickly, using existing systems and experience. Developmental efforts can instead be focused on Mars technologies.

That is not to say there is not a place for commercial deliveries, alongside SLS delivering large diameter and large mass pieces. ISS experience has shown that commercial resupply is a viable paradigm. The combination of the two – SLS and commercial launch vehicles – creates the best path forward to a viable lunar outpost.

IX. Conclusion

SLS, Orion, and the planned Lunar Orbital Platform – Gateway combine to make returning humans to the surface of the moon a winning proposition. The Gateway would serve as the jumping off point for lunar missions, as well as a base for telerobotic operations on the lunar surface. SLS and Orion would deliver the lunar lander and crew for lunar surface missions. With this in place, a wide variety of lunar missions could be planned, resulting in sustained human presence on the lunar surface at a lunar outpost. The experience gained from the lunar outpost missions would be invaluable to the eventual missions to Mars.

References

[1] NASA, "NASA's Journey to Mars: Pioneering Next Steps in Space Exploration", NP-2015-08-2018-HQ, October 2015, [Online] Available: https://www.nasa.gov/sites/default/files/atoms/files/journey-to-mars-next-steps-20151008_508.pdf

[2] Craig, D. A., Troutman, P., and Hermann, N. A., "Pioneering Space through an Evolvable Mars Campaign," *AIAA SPACE 2015 Conference and Exposition, Pasadena, CA,* 2015. AIAA 2015-4409. DOI: 10.2514/6.2015-4409

[3] Goodliff, K., Troutman, P., Craig, D., Caram, J., and Herrmann, N., "Evolvable Mars Campaign 2016 – A Campaign Perspective," *AIAA SPACE 2016 Conference and Exposition, Long Beach, CA, 2016*. AIAA 2016-5456. DOI: 10.2514/6.2016-5456

[4] NASA, "New Space Policy Directive Calls for Human Expansion Across Solar System," NASA Release 17-097, Dec. 11, 2017, [Online] Available: https://www.nasa.gov/press-release/new-space-policy-directive-calls-for-human-expansion-across-solar-system

[5] "ESA's Guide to the Moon," ESA, April 22, 2016. [Online] Available: http://www.esa.int/Our_Activities/Human_Spaceflight/ESA_s_guide_to_the_Moon

[6] NASA. "NASA Completes Review of First SLS, Orion Deep Space Exploration Mission," Nov. 8, 2017. [Online] Available: https://www.nasa.gov/feature/nasa-completes-review-of-first-sls-orion-deep-space-exploration-mission. Accessed May 21, 2018.

[7] NASA, "Orion Overview," Aug. 3. 2017. [Online] Available: https://www.nasa.gov/exploration/systems/orion/about/index.html

[8] NASA, "Orion Quick Facts", FS-2014-08-004-JSC, Aug. 21, 2014. [Online] Available: https://www.nasa.gov/sites/default/files/fs-2014-08-004-jsc-orion_quickfacts-web.pdf

[9] Hadfield, C. A., "ISS – Enabling Exploration through Docking Standards," *NASA International Space Station and Mars Conference, Washington DC*, April 2011. [Online] Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110016704.pdf

[10] Percy, T., McGuire, M., and Polsgrove, T., "Combining Solar Electric Propulsion and Chemical Propulsion for Crewed Missions to Mars," *IEEE Aerospace Conference, Big Sky, MT*, 2015. [Online] Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150006952.pdf

[11] Chai, P. R., Merrill, R. G., and Qu, M., "Mars Hybrid Propulsion System Trajectory Analysis Part I: Crew Missions," *AIAA SPACE 2015 Conference and Exposition, Pasadena, CA*, 2015. AIAA-2015-4443. DOI: 10.2514/6.2015-4443

[12] Brauer, G. L., Cornick, D. E., and Stevenson, R., "Capabilities and Applications of the Program to Optimize Simulated Trajectories (POST)," 1977, NASA CR-2770, [Online] Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/1+9770012832.pdf

[13] NASA. "Copernicus Trajectory Design and Optimization System," Oct. 1 2016. [Online] Available: https://www.nasa.gov/centers/johnson/copernicus/index.html . Accessed September 1, 2017.

[14] Crusan, J. C., et al., "Deep Space Gateway Concept: Extending Human Presence into Cislunar Space," *IEEE Aerospace Conference 2018, Big Sky, MT*, 2018. 2018-8.0101.

[15] Whitley, R. and Martinez, R. "Options for Staging Orbits in Cislunar Space," *IEEE Aerospace Conference, Big Sky, MT*, 2016. [Online] Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150019648.pdf

[16] Foust, J., "House Bill Keeps Europa Clipper on track Despite Launch Vehicle Uncertainties," SpaceNews, May 10, 2018. [Online] Available: http://spacenews.com/house-bill-keeps-europa-clipper-on-track-despite-launch-vehicle-uncertainties/ . Accessed May 21, 2018.

[17] Donahue, B. and Sigmon, S., "Space Launch System: Bleock 1B Configuration: Development and Mission Opportunities," *53rd Joint Propulsion Conference, Atlanta, GA*, 2017. AIAA 2017-4709. DOI: 10.2514/6.2017-4709

[18] NASA, "FY2019 Budget Estimates," Feb. 12, 2018. P. 141. [Online] Available: https://www.nasa.gov/sites/default/files/atoms/files/nasa_fy_2019_budget_overview.pdf . Accessed May 21, 2018.

[19] Gerstenmaier, W. H., "Progress in Defining the Deep Space Gateway and Transport Plan," presented to the NASA Advisory Council, March 28, 2017. [Online] Available: https://www.nasa.gov/sites/default/files/atoms/files/nss_chart_v23.pdf

[20] NASA, "Deep Space Gateway to Open Opportunities for Distant Destinations," Mar 28. 2017. [Online] Available: https://www.nasa.gov/feature/deep-space-gateway-to-open-opportunities-for-distant-destinations. Accessed September 20, 2017.
[21] Post, K., Kamath, U., and Loucks, M., "Lunar Proving Ground Logistics Resupply -- Performance Considerations," *57th International Astronautical Conference, Guadalajara, Mexico*, 2016.
[22] Berger, E. "NASA Asks for Eruopa Lander Science Experiments – and that's a Big Deal," Ars Technica. May 18, 2018. [Online] Available: https://arstechnica.com/science/2018/05/nasa-asks-for-europa-lander-science-experiments-and-thats-a-big-deal/. Accessed May 21, 2018.
[23] Donahue, B. B., Caplin, G. N., Smith, D. B., Behrens, J., and Maulsby, C., "Lunar Lander Concepts for Human Exploration," *Journal of Spacecraft and Rockets*, Vol. 45, No. 2, 2008, pp. 383-393.
DOI: 10.2514/1.29270
[24] Hofstetter, W. K., Wooster, P. D., and Crawley, E. F., "Analysis of Human Lunar Outpost Strategies and Architectures," *AIAA SPACE 2007 Conference & Exposition, Long Beach, CA,* 2007. AIAA 2007-6276.
DOI: 10.2514/6.2007-6276
[25] Donahue, B. B., Caplin, G. N., and Smith, D. B., "Lunar Lander Concept Design for the 2019 NASA Outpost Mission," *AIAA SPACE 2007 Conference & Exposition, Long Beach, CA,* 2007. AIAA 2007-6175.
DOI: 10.2514/6.2007-6175
[26] Mills, G. A., and Riesco, M. E., "Propellant Selection for the Lunar Lander Ascent Stage," *AIAA SPACE 2008 Conference & Exposition, San Diego, CA*, 2008. AIAA 2008-7906.
DOI: 10.2514/6.2008-7906
[27] Rucker, M. A., et al., 'Solar Versus Fission Surface Power for Mars," *AIAA SPACE 2016 Conference & Exposition, Long Beach, CA*, 2016. AIAA 2016-5452.
DOI: 10.2514/6.2016-5452
[28] NASA, "Demonstration Proves Nuclear Fission System Can Provide Space Exploration Power," Release 18-031, May 2, 2018. [Online] Available: https://www.nasa.gov/press-release/demonstration-proves-nuclear-fission-system-can-provide-space-exploration-power. Accessed May 21, 2018.
[29] NASA, "The ATHLETE Rover," Aug. 7, 2017. [Online] Available: https://www.nasa.gov/multimedia/imagegallery/image_feature_748.html. Accessed March 21, 2018.
[30] Joshi, M. "Villages on the Moon: ISRO to Build Lunar Base with 3D Printing," *Computerworld*, Mar. 13, 2018. [Online] Available: http://www.computerworld.in/news/moon-isro-build-lunar-base-3d-printing. Accessed Mar. 21, 2018.
[31] Duggan, M., Engle, J., Moseman, T., Simon, X, and Manyapu, K., "A Crewed Lunar Lander Concept Utilizing the SLS, Orion, and the Cislunar Deep Space Gateway," *IEEE Aerospace Conference 2018, Big Sky, MT*, 2018. 2018-8.0106.
[32] Hume, A., "NASA Laser Communications to Provide Orion Faster Connections," NASA, Dec. 15, 2017. [Online] Available: https://www.nasa.gov/feature/goddard/2017/nasa-laser-communications-to-provide-orion-faster-connections. Accessed March 21, 2018.
[33] Simon, M. et al, "NASA's Advanced Exploration Sytems Mars Transit Habitat Refinement Point of Departure Design," *IEEE Aerospace Conference, Big Sky, MT*, 2017. [Online] Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170002219.pdf
[34] McGuire, M. L., et al. "Potential Cislunar and Interplanetary Proving Ground Excursion Trajectory Concepts," *IEEE Aerospace Conference, Big Sky, MT,* 2016. [Online] Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160003117.pdf
[35] NASA JPL, "Near Earth Object Program," [Online]. Available: http://neo.jpl.nasa.gov/risk/ 2000sg344.html. Accessed 6 October 2016
[36] NASA JPL, "JPL Small-Body Database Browser," [Online]. Available: http://ssd.jpl.nasa.gov/sbdb.cgi?sstr=2000+SG344; orb=1. Accessed 06 October 2016.
[37] Kutter, B. F., Zegler, F., Barr, J., Bulk, T., and Pitchford, B., "Robust Lunar Exploration Using an Efficient Lunar Lander Derived from Existing Upper Stages," *AIAA SPACE 2009 Conference & Exposition, Pasadena, CA,* 2009. AIAA 2009-6566.
DOI: 10.2514/6.2009-6566
[38] Morring, F., "Blue Origin Developing 10,000-lb Lunar Polar Lander," *Aviation Week & Space Technology*, Mar. 3, 2017. [Online] Available: http://aviationweek.com/space/blue-origin-developing-10000-lb-lunar-polar-lander. Accessed Mar. 21, 2018.
[39] Grossman, D., "China, European Space Agency Plan to Collaborate on 'Moon Village'," *Popular Mechanics*, Apr. 26, 2017. [Online] Available: https://www.popularmechanics.com/space/moon-mars/a26225/china-european-space-agency-collaborate-moon-village/. Accessed Mar. 21, 2018.
[40] Zolfagharifard, E. "Russia's plan to conquer the moon: Nation will send 12 cosmonauts to lunar surface ahead of creating a permanent base by 2030," *Daily Mail*, June 22, 2016. [Online] Available: http://www.dailymail.co.uk/sciencetech/article-3653942/Russia-s-plan-conquer-moon-Nation-send-12-cosmonauts-lunar-surface-ahead-creating-permanent-base-2030.html. Accessed Mar. 21, 2018
[41] Jeffries, S., Collins, T., Dwyer Cianciolo, A., and Polsgrove, T., "Impacts of Launch Vehicle Fairing Size on Human Exploration Architectures," *IEEE Aerospace Conference 2017, Big Sky, MT,* 2017. [Online] Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170002220.pdf.