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NASA's Human Landing System: A Sustaining Presence on the Moon

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Abstract

For more than a decade, efforts have been ongoing at NASA's Marshall Space Flight Center (MSFC) in Huntsville, Alabama, to land humans and cargo on planetary bodies like the Moon and Mars and today this work continues under the Center's Lander Programs (LP) office. In August of 2019, NASA stood up the Human Landing System (HLS) program to be responsible for spacecrafts that will land astronauts on the Moon under Artemis. Work is well underway with the historic Artemis III mission to land the first Americans on the lunar surface in more than 50 years through the Appendix H Option A [1] contract with SpaceX. In November, NASA awarded SpaceX an Option B modification to its existing HLS Appendix H contract, which will further develop its Starship HLS to meet NASA's sustaining lander requirements for lunar missions beyond Artemis III.

In September of 2022, NASA issued an HLS Sustaining Lunar Development solicitation under the NextSTEP-2 Appendix P Broad Agency Announcement [2] asking a second provider, in addition to SpaceX, to develop and demonstrate a lander that meets the program's extended set of requirements for missions beyond Artemis III. Under the umbrella of Sustaining Lunar Development [3], these requirements will meet NASA's needs for recurring, long-term access to the lunar surface. Proposals were received from industry late last year and NASA is planning to award an Appendix P contract in the summer of 2023.

This paper will provide an update of the Lander Program office's progress and will discuss how the program is bridging from the initial demonstration phase of development for the Human Landing System program to the Sustaining Lunar Development phase. The paper will include publicly available information on SpaceX's Starship HLS design as well as near-term and future milestones for HLS and the Artemis program.

Acronyms/Abbreviations

Extravehicular activities (EVAs), Environmental Control Life Support System (ECLSS), government task agreement (GTA), Human Landing System (HLS), Low Earth orbit (LEO), Lunar Orbit Checkout Review (LOCR), National Aeronautics and Space Administration (NASA), Near-Rectilinear Halo Orbit (NRHO), subject matter expert (SME), Space Launch System (SLS), Sustaining Lunar Development (SLD), trans-lunar injection (TLI)

1. Introduction

NASA is on a path to get the first Americans back to the Moon again and the agency has selected two commercial partners, SpaceX and Blue Origin, to build separate commercial human landers for the mission. Both partners will safely carry astronauts to the lunar surface for Artemis III, IV, and V. SpaceX will develop the Starship HLS (Figure 1), the first commercial human lander that will carry the first two American astronauts to the lunar surface for Artemis III. Late last year, SpaceX under a contract modification to Appendix H, was awarded additional work under Option B [4], to develop a second commercial human lander that meets NASA's requirements for long-term human exploration of the Moon for Artemis IV.

In May 2023, NASA awarded the Blue Origin-led team the Appendix P contract [5] which will see the development of another commercial lander (Figure 2) that will meet human landing system requirements for recurring astronaut expeditions to the lunar surface, including docking with Gateway.

Fig. 1. Artist depiction of the Starship HLS (Image: SpaceX)

Artemis missions will see the agency's powerful Space Launch System (SLS) rocket launch four astronauts aboard the Orion spacecraft for their multi-day journey to lunar orbit. Artemis III missions will see two crew members transfer from Orion to the SpaceX Starship HLS for the final leg of their journey to the surface of the Moon. For Artemis IV and V, the lander and Orion will dock with Gateway for crew transfer. The duration of time spent on the Moon surface will vary for each Artemis mission, but the initial trips will last approximately one week while later trips to the lunar surface could last nearly a month. Once completed, astronauts will board the lander for their short trip back to orbit where they will return to Orion for Artemis III or Gateway for future Artemis missions. Once there, they will meet up with fellow crew members and head back to Earth on Orion.

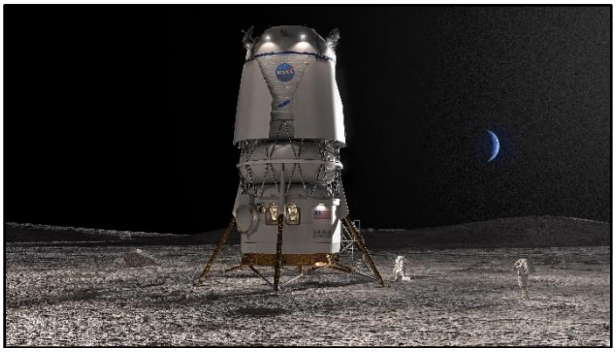

Fig. 2. Artist depiction of Blue Moon HLS (Image: Blue Origin)

Both SpaceX and Blue Origin are working closely with NASA experts to inform their lander designs and to ensure they met NASA's performance requirements and human spaceflight standards. A key tenet for safe systems, these agreed-upon standards range from areas of engineering, safety, health, and medical technical areas.

This paper will provide a look at lander development by both SpaceX and Blue Origin under the Human Landing System program. It will also include publicly available information on both SpaceX and Blue Origin's lander designs as well as near-term and future milestones for HLS and the Artemis program.

2. Artemis III – Initial Lander Development

2.1. Mission Overview and Concept of Operations

Artemis III will mark humanity's return to the Moon in more than 50 years, with NASA making history by sending the first humans to the lunar South Pole to explore.

SpaceX's Starship HLS will be prepositioned in Near-Rectilinear Halo Orbit (NRHO) to receive crew. To accomplish this, SpaceX will start by launching a storage depot variant of Starship to Earth orbit, followed by a series of reusable tanker Starship variants that will carry propellant to the storage depot. The Starship HLS will launch and be fueled by the depot before executing a translunar injection (TLI) engine burn, traveling approximately six days to NRHO where it will perform a Lunar Orbit Checkout Review (LOCR) and await the Artemis III crew.

The crew of four will launch to NRHO onboard the Orion spacecraft atop the SLS rocket. Orion will dock with the Starship HLS and two astronauts, and their supplies will board Starship, leaving the other two to remain in Orion. Orion will undock and back away from Starship and remain in NRHO. Starship will then descend to the lunar surface for an approximate 6.5 day stay where crew will do scientific work inside Starship and conduct a series of moonwalks to take pictures and video, survey geology, retrieve samples, and collect other data.

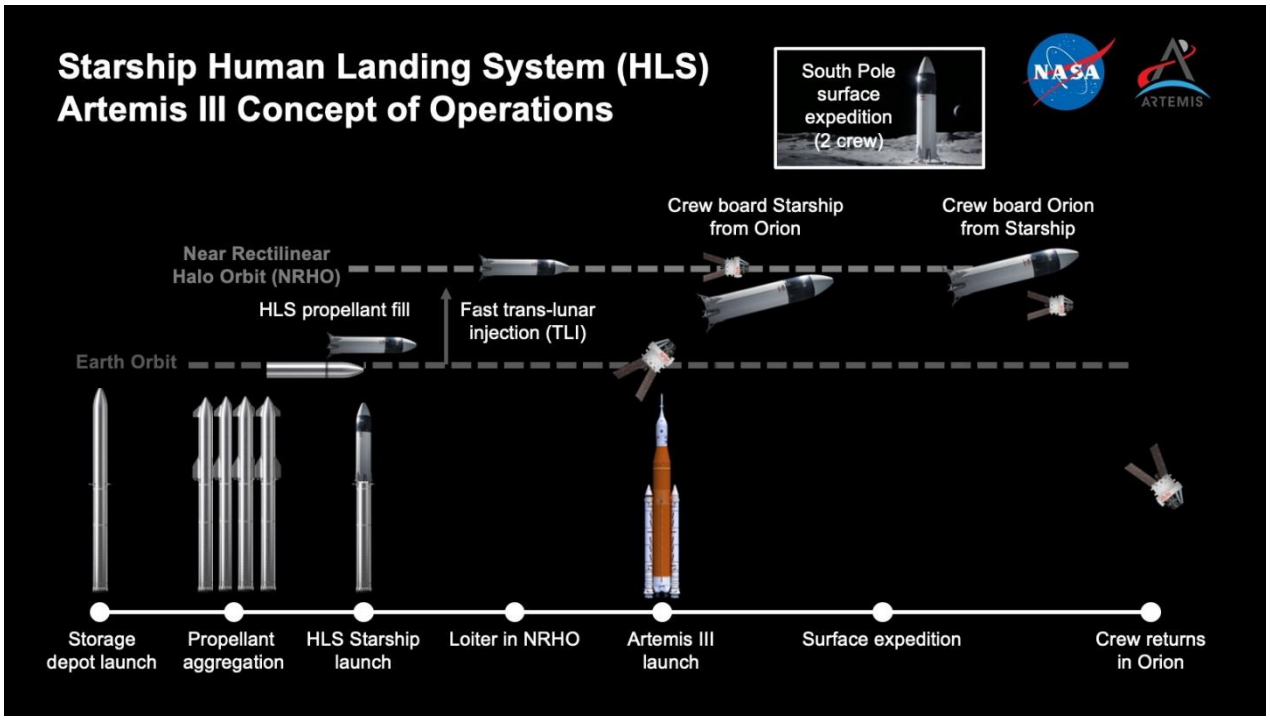

Fig. 3. Starship HLS Artemis III Concept of Operations

When the surface expedition is complete, the Starship HLS will ascend from the lunar surface, carrying the two astronauts back to NRHO to reunite with their crewmates in Orion. At this point in Artemis III, the Starship HLS mission is complete. The Artemis III concept of operations is depicted in Figure 3.

2.2. Development Progress

Since being selected for the Option A period in April 2021 [6] as the Artemis III Human Landing System, SpaceX has made significant progress on the Starship HLS.

SpaceX intends to utilize three variants of the Starship concept to support returning humans to the surface of the Moon in the Artemis III mission. All three variants (Figure. 4) will be boosted to orbit by a Super Heavy Booster first stage, which is 9m in diameter, 70m long, and is powered by 33 SpaceX Raptor engines.

Fig. 4. Starship Vehicle Configurations for NASA HLS

Leveraging SpaceX's commercial Starship system which consists of a Starship and a Super Heavy Booster, SpaceX has successfully conducted a 10km sub-orbital flight of the Starship and successfully launched an integrated Starship and Booster in April 2023, greatly increasing knowledge of integrated vehicle performance and the concept of operations.

In May of 2021, SpaceX successfully completed a 10 km suborbital flight and landing of the Starship SN15 spacecraft (Figure 5). SpaceX then turned its focus to conducting the first orbital flight of the integrated Starship system (Spacecraft + Booster).


Fig 5. Starship SN15 test flight landing (Image: SpaceX)

Leading to the first orbital flight, SpaceX conducted several activities on the booster and ship flight set. The activities in preparation for flight included several Raptor engine acceptance tests (33 engines for Booster 7 and 6 for Ship 24), tank sections cryogenic proof and qualification testing, booster and ship engine spin prime testing, booster & ship hot fire testing, and launch wet dress rehearsals.

The integrated Starship vehicle launched on April 20, 2023, successfully lifting off the pad (Figure. 6), cleared the tower and proceeded to rise for over three minutes.

Ultimately, the vehicle had to be commanded to destruct. The attempt provided a wealth of valuable information on overall vehicle performance which is now being incorporated into design refinements and changes to the concept of operations.

Fig. 6. SpaceX Integrated Flight Test, April 2023. (Image: SpaceX)

Aside from the important attention on the first orbital launch and propellant aggregation development, SpaceX and the HLS program are focused on several other activities towards the further development of the Artemis III lunar lander. Astronaut crews have been conducting early development training activities to assess landing trajectories and aspects of vehicle piloting during landing. Material flammability testing is being conducted to assess the flammability aspects in the cabin atmosphere environment and accounting for lunar gravity.

SpaceX has also developed a crew cabin mock up to test aspects of the Environment Control Life Support Systems (ECLSS) and thermal control system. SpaceX has also conducted development testing and analyses on crew displays, crew elevator, hot gas reaction control system, solar array deployment, thermal and micro meteoroid debris protection tiles, landing legs, docking mechanisms, landing software & sensors, medical systems, and recently conducted a six second static fire of its Super Heavy Booster (Figure. 7.) The wider NASA team has conducted assessments on mission planning and the evaluation of landing site selection to maximize science goals.

Fig. 7. Super Heavy Booster's 33 Raptor static fire, August 2023. (Image: SpaceX)

3. Artemis IV – Transition to Sustaining

3.1. Requirement Differences from Initial

The HLS program is concurrently developing an initial and sustaining landers. The primary objective of the initial lander is to return mankind to the moon and build upon those capabilities and further enable the continual exploration of the Moon.

A primary difference in the two landers is the way they will be used. The initial lander will rendezvous directly with the Orion spacecraft in lunar orbit and be used to perform two-person, seven-day mission on the Moon's surface independent of any other assets on the surface.

For sustained missions, the Gateway space station orbiting the Moon is used as a hub to transfer crew from Orion to the HLS. While the sustained lander can also accomplish independent missions, it is designed to deliver four astronauts to the surface where they can then use pre-placed habitats and rovers at the southern pole area to live for up to 33 days before returning to the lander ascending back to Gateway. While the initial lander will be used for missions to the southern pole, the sustained lander has capabilities to explore other parts of the lunar surface independent of pre-placed assets.

The increased surface duration and scientific opportunities dictates increased capabilities for the sustained lander. The initial lander will not operate in full lighting conditions, limiting the time period that a mission can take place. The sustained lander can operate during lunar night conditions for up to 230 hours. With

pre-placed surface assets, the sustained landing accuracy has increased from 100 meters to 50 meters. The sustained lander also has the capability to remotely operate the surface assets. The scientific objective of the initial mission focuses on returning rock samples. The sustained lander will enable a freezer to be flown and allow core samples to be collected and returned. The sustained mission will also have the capability to record video of the ascent of the lander off the lunar surface.

3.2 Mission Overview and Concept of Operations

The expanded capability required in our sustained phase procurements allows for growth in the types of missions we can fly. We'll be able to continue two crew sortie missions to the south pole and carry four crew members for longer duration excursion missions.

The first flight of this sustained capability will be Artemis IV. In this mission we'll see the Starship integrated lander conduct a two-crew sortie mission to the south pole, with Earth launch and propellant transfer operations similar to Artemis III, but this time docking with NASA's Gateway station in NRHO to pick up two crew members and carry them to the lunar surface and back.

3.4 Transition to Sustaining

While Artemis III is the focus of the current efforts for both NASA and SpaceX, attention to future missions is also being considered. In addition to being awarded the Appendix H Option A (Initial Capability - Artemis III), SpaceX was also selected to provide the vehicle for Appendix H Option B (Sustaining Capability) which will be flown as part of the Artemis IV mission.

Key differences in Artemis III and Artemis IV such as initial destination (Orion for Artemis III and Gateway for Artemis IV), crew size (two for Artemis III and four for Artemis IV) and mission duration (10 days For Artemis III and 30 for Artemis IV) will require changes to significant Starship systems such as the environmental control and life support system, crew cabin layout and guidance and navigation control for increased landing accuracy.

To minimize changes in vehicle configuration and make the design and development of the vehicle as common as possible, NASA and SpaceX are working together to implement many Artemis IV requirements as the Starship development progresses.

As was done during the Appendix H base period, a detailed requirements review, and adjudication process was conducted to understand the differences between the two missions and the impact on vehicle design and configuration. The result being that, where possible, the sustaining requirements will be implemented on the initial capability vehicle. Maximizing vehicle commonality will pay great benefits in future vehicle builds by eliminating the need for additional testing, evaluation, and verification of different vehicle designs. This will also allow SpaceX to accelerate vehicle builds to help ensure availability and on time delivery for mission integration.

4. Artemis V – Blue Origin's Answer to Sustaining

4.1. Mission overview & Concept of Operations

The Blue Origin-led team, which includes Astrobotic, Boeing, Draper, Honeybee Robotics, and Lockheed Martin, will design, develop, test, and verify its Blue Moon lander to meet NASA's human landing system requirements for recurring astronaut expeditions to the lunar surface, including docking with Gateway. In addition to design and development work, the contract includes one uncrewed demonstration mission to the lunar surface before a crewed demonstration mission for Artemis V in 2029.

The Artemis V mission will include separate elements of Blue Origin's architecture, including the cislunar transporter, the lander and the refueler, which will launch separately on New Glenn rockets. The lander will perform a TLI to NRHO while the transporter remains in LEO to be fueled by the refueler. After fueling, the transporter will head to Moon's orbit where it will dock with the lander to transfer propellant. After the lander is fueled by the transporter, the two vehicles separate, and the lander heads for Gateway while the transporter returns to LEO for future refueling operations.

Once the lander is ready to receive crew, four astronauts onboard Orion are launched on an SLS rocket out to NRHO to dock with Gateway. Once Orion docks with Gateway, two astronauts will transfer to Blue Origin's human landing system for the trip to the Moon's South Pole region where they will conduct science and exploration activities. Artemis V is at the intersection of demonstrating NASA's initial lunar exploration capabilities and establishing the foundational systems to support recurring complex missions in lunar orbit and on the surface as part of the agency's Moon to Mars exploration approach. The Artemis V concept of operations is depicted in Figure 8.

4.2. Insight, Collaboration and Government Task Agreements

Under the Appendix P contract with Blue Origin, and all HLS contracts in general, the contractor is required to provide the Government insight into their HLS-related activities. The HLS program uses insight teams as part of the approach whereby the Government will gather

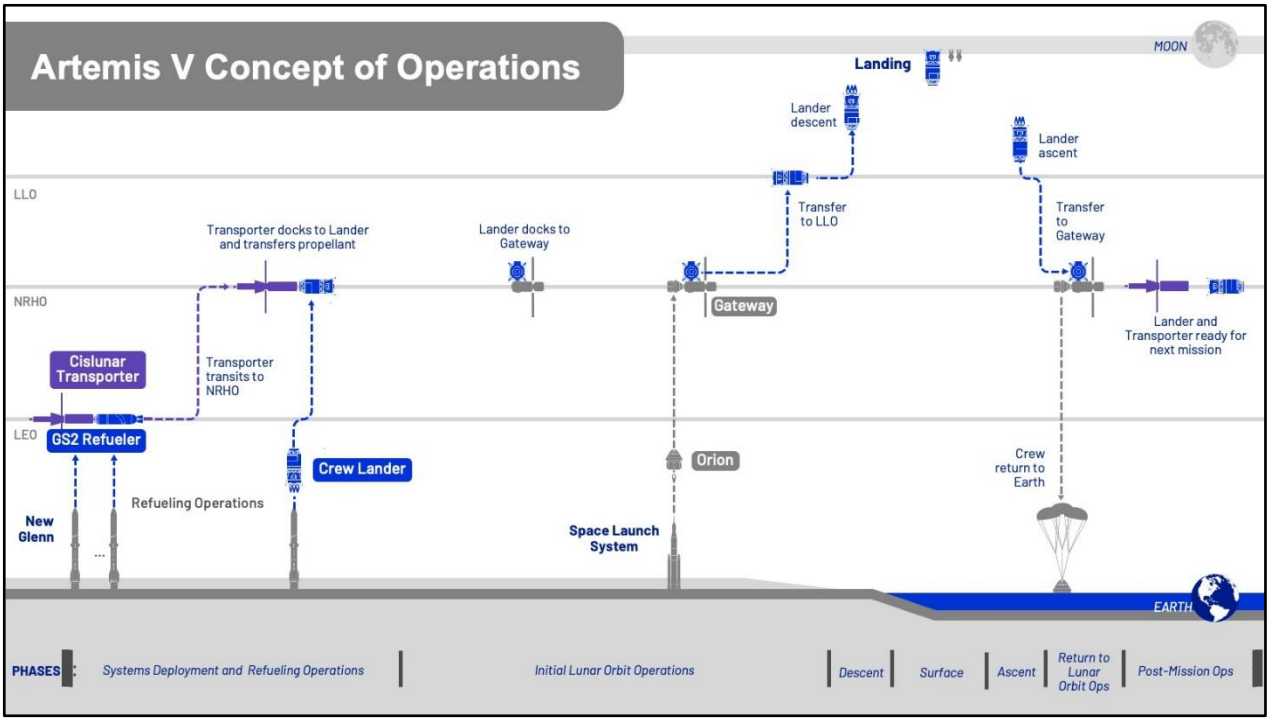

Figure 8. Artemis V Concept of Operations

information regarding the Blue Origin design to aid in certifying the integrated lander system for human use. The HLS program uses a risk-based insight construct focusing on targeted areas of program concern. This ensures that Blue Origin is not being overly burdened by excessive insight activity in low-risk areas.

In addition to the contracted deliverables and reviews, the interactions between Blue Origin and the Government will provide NASA sufficient insight into the activities associated with the HLS integrated lander design, development, manufacture, integration, test, verification, validation, certification, and operation while still allowing Blue Origin, its subcontractors, and vendors to maintain the efficiencies and effectiveness of their commercial processes.

Additionally, NASA has personnel with unique expertise and experience that are made available, within the Appendix P contract requirements, to Blue Origin. Blue Origin may request the use of full-time NASA personnel for targeted advisory support during contract performance, which is termed "collaboration."

Collaboration allows Blue Origin to use this NASA expertise to advise on and augment work that is being accomplished in high-risk technical areas and provides a focused, in-depth insight into their design, development, manufacturing, testing and operations in a particular technical area, risk, or issue.

For Appendix P, Blue Origin has requested approximately 56 collaboration tasks in the base period of the contract. Examples of areas where Blue Origin is seeking collaborative tasks with NASA include, but are not limited to, cryogenic fluid management and transfer, ionizing radiation, plume surface interaction, lunar landing analyses, and propulsion.

Lastly, since NASA possesses unique property, facilities, and services, NASA allowed Blue Origin to request the use of those properties, facilities, and services to perform a portion of the in-scope contract work through Government Task Agreements (GTAs). GTAs can be used to provide testing, space communications, transportation services, and manufacturing utilizing NASA facilities. Blue Origin, at this point, has planned GTAs across six NASA Centers and the Jet Propulsion Laboratory, for the use of 31 facilities and services on the Appendix P contract.

4.3 A Nod to Services

All of the work undertaken for the Artemis III, Artemis IV, and Artemis V missions will help pave the way to a future solicitation for recurring lunar transportation services for taking astronauts to and from the Moon's surface.

5. Conclusions

Responsible for the transportation of humans between lunar orbit and the lunar surface, the Human Landing System program is at the center of Artemis, designed to yield ground-breaking science, develop, and utilize lunar surface resources, and leverage what we learn at the Moon for future Mars missions.

NASA is committed to establishing a sustained lunar presence, through both Appendix H and Appendix P

contracts, while working closely with SpaceX and the Blue Origin-led team. The HLS program will facilitate the rapid development and demonstration of the human landing system that will deliver the first woman, and in later missions, the first person of color, to the Moon. The HLS capability demonstrated during the Artemis III mission will evolve into a safe and affordable long-term approach to accessing the lunar surface for future, more sustainable, Artemis missions.

Through Artemis, NASA and its international and commercial partners will establish a cadence of trips to the Moon where American astronauts will conduct science investigations, technology demonstrations, and establish a long-term presence to prepare for humanity's next giant leap – sending astronauts on a roundtrip to Mars.

The HLS program continues its hard work toward achieving major agency milestones as NASA embarks on its mission to explore deep space and beyond this decade and into the future.

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