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NASA's Initial Artemis Human Landing System

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Abstract

In April 2020, NASA announced the selection of three companies to begin the initial phase of development of human landing systems to take the first woman and the first person of color to the lunar surface through NASA's Artemis lunar exploration program. The selected companies were a Blue Origin-led team with Lockheed Martin, Northrup Grumman, and Draper; Dynetics (a Leidos company); and SpaceX. Contracts were awarded shortly after, kicking off a ten-month base period during which NASA worked closely with each company to finalize functional and performance requirements, confirm lander development standards, and establish baseline designs, schedules, and management plans for contract execution and human spaceflight certification. At the end of the base period, in the Spring of 2021, NASA awarded a single follow-on Option A contract to SpaceX to continue their work on Human Landing System (HLS) Starship development. Currently NASA and SpaceX are working collaboratively on Option A which will ultimately culminate in one uncrewed and one crewed mission to the lunar surface under Artemis III.

This paper will provide a look at the Option A phase of development for the Human Landing System Program, including publicly available information on SpaceX's HLS Starship design as well as near-term and future milestones for HLS and the Artemis program.
Keywords: Artemis, Human Landing System, NASA, Option A, SpaceX, Starship

Acronyms/Abbreviations

Chief SMA Officer (CSO), Crew Survivability Analysis Report (CSAR), Design, Development, Test and Evaluation (DDT&E), Eextravehicular activities (EVAs), Environmental Control Life Support System (ECLSS), Fault Tree Analysis (FTA), government task agreement (GTA), HLS Safety and Engineering Review Panel (HSERP), Human Landing System (HLS), Interface Control Documents (ICDs), Interface Requirements Document (IRD), Micro Meteoroid Orbital Debris (MMOD), Mishap Preparedness and Contingency Plan (MPCP), National Aeronautics and Space Administration (NASA), Near-Rectilinear Halo Orbit (NRHO), Probability Risk Assessment (PRA), Program System Requirements Document (PSRD), Safety & Mission Assurance (SMA), subject matter expert (SME), Space Launch System (SLS), Sustaining Lunar Development (SLD), Technical Interchange Meetings (TIM), trans-lunar injection (TLI)

1. Introduction

NASA is getting ready to send astronauts to explore more of the Moon as part of the Artemis program, and the agency selected SpaceX to continue development of the first commercial human lander that will safely carry the next two American astronauts to the lunar surface. At least one of those astronauts will make history as the first woman on the Moon. Another goal of the Artemis program includes landing the first person of color on the lunar surface.

The agency's powerful Space Launch System (SLS) rocket will launch four astronauts aboard the Orion spacecraft for their multi-day journey to lunar orbit. There, two crew members will transfer to the SpaceX Starship human landing system for the final leg of their journey to the surface of the Moon. After approximately a week exploring the surface, they will board the HLS Starship for their short trip back to orbit where they will return to Orion and their colleagues before heading back to Earth.

The firm-fixed price, milestone-based contract total award value is $2.89 billion.

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

SpaceX worked closely with NASA experts during the Appendix H base period to inform its lander design and ensure it meets 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 the following Option A phase of development for the Human Landing System program, including publicly available information on SpaceX's HLS Starship design as well as near-term and future milestones for HLS and the Artemis program.

2. Option A Status

The Appendix H base period [1] focused on establishing agreements between NASA and our three industry providers regarding Design and Construction Standards for both Engineering and Safety & Mission Assurance (S&MA) as well as Health and Medical Requirements. The base period also supported the advancement of each provider's design concepts in anticipation of the Option A competition and selection.

In late April 2021, the SpaceX Starship concept was selected [2] as the single award winner for the Human Landing System Appendix H Option A contract. The SpaceX HLS concept leverages the development of their commercial Starship system which consists of a Starship Spacecraft and a Super Heavy Booster.

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. 2) 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.

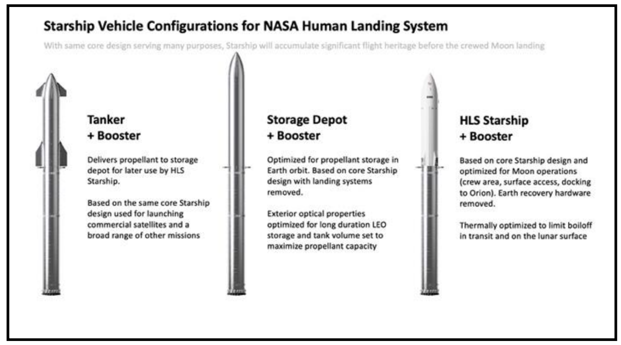

Fig. 2. The three Starship variants that will be utilized for Artemis III are Tanker Starships to transport propellent, a Storage Depot to store the propellent in Earth orbit, and the HLS Starship that will travel to the Moon.

In May of 2021, SpaceX successfully completed a 10 km suborbital flight and landing of the Starship SN15 spacecraft Figure 3. SpaceX now turns its focus to conducting the first orbital flight of the integrated Starship system (Spacecraft + Booster) which will come in the next year.

Fig. 3. Starship SN15 test flight landing (Image: SpaceX)

2.1. Artemis III HLS Mission Overview

Under the proposed Artemis III HLS Starship mission architecture, the Super Heavy Booster will first deliver a

Depot Starship to Earth orbit. This will be followed by several flights of Tanker Starships, which will deliver mission-critical methane and oxygen propellants to the Depot. Once a sufficient load of propellant has been delivered to the Depot, the Super Heavy Booster will carry the HLS Starship to orbit. The 9m diameter, 50m long HLS Starship will rendezvous with the orbiting Depot and take on the propellants required to execute the lunar landing mission. Once fully loaded, the HLS Starship, powered by six SpaceX Raptor engines, will perform trans-lunar injection (TLI) and begin its journey to the pre-defined Near-Rectilinear Halo Orbit (NRHO) where it will complete vehicle systems checkouts and loiter waiting for the Orion spacecraft, which will carry four crewmembers and be launched on the Space Launch System (SLS). Orion will dock with Starship and two crewmembers will transfer into the vehicle. With crew onboard, the HLS Starship will undock from Orion, de-orbit, and conduct a landing near the Moon's South Pole. The crew may conduct multiple extravehicular activities (EVAs) and, after several days on the surface, the HLS Starship will ascend back to NRHO and rendezvous with Orion. Once the crew transfers back to Orion, HLS Starship will undock and complete its disposal. At this point the NASA mission with Starship will be complete. Orion will then carry the crew safely back to Earth. The Artemis III HLS concept of operations is depicted in Figure 4.

2.2. Design and Development

Under the Option A work of the last year, several key design efforts have continued to mature. As part of the HLS Starship development activities, SpaceX has conducted design reviews and/or testing of various systems. The Raptor engine design has undergone numerous tests, including evaluations of performance under lunar landing throttle profiles. Aft docking mechanism designs—key to the SpaceX propellant transfer architecture - have continued to mature. Testing and analysis have also been performed for the Starship Micro Meteoroid Orbital Debris (MMOD)/Thermal Protection Tiles as well as the Environmental Control Life Support System (ECLSS), Thermal Control System, Landing Software and Sensor System, and Software Architecture.

Detailed descent and ascent trajectories are also under development. For descent, the unique lighting environment created by the perpetual low sun angles of the South Pole region [3] requires that extra effort be put into the development of the navigation and sensor systems that will ensure a safe landing. In the Apollo missions, equatorial landing sites ensured that the sun traversed the sky-high overhead for the duration of the astronauts' stay on the lunar surface. At the South Pole, the sun remains low on the horizon, casting long shadows and creating extended periods of darkness in the shadow of surface features. The same phenomenon that creates the permanently shadowed regions, which draw the science community to this previously unexplored region of the Moon, also make site selection and hazard avoidance more complicated, and special attention has been focused on this as the HLS Starship design matures.

Additional focus has also been placed on the development of the single spacecraft-to-spacecraft interface that exists in this architecture: the docking of

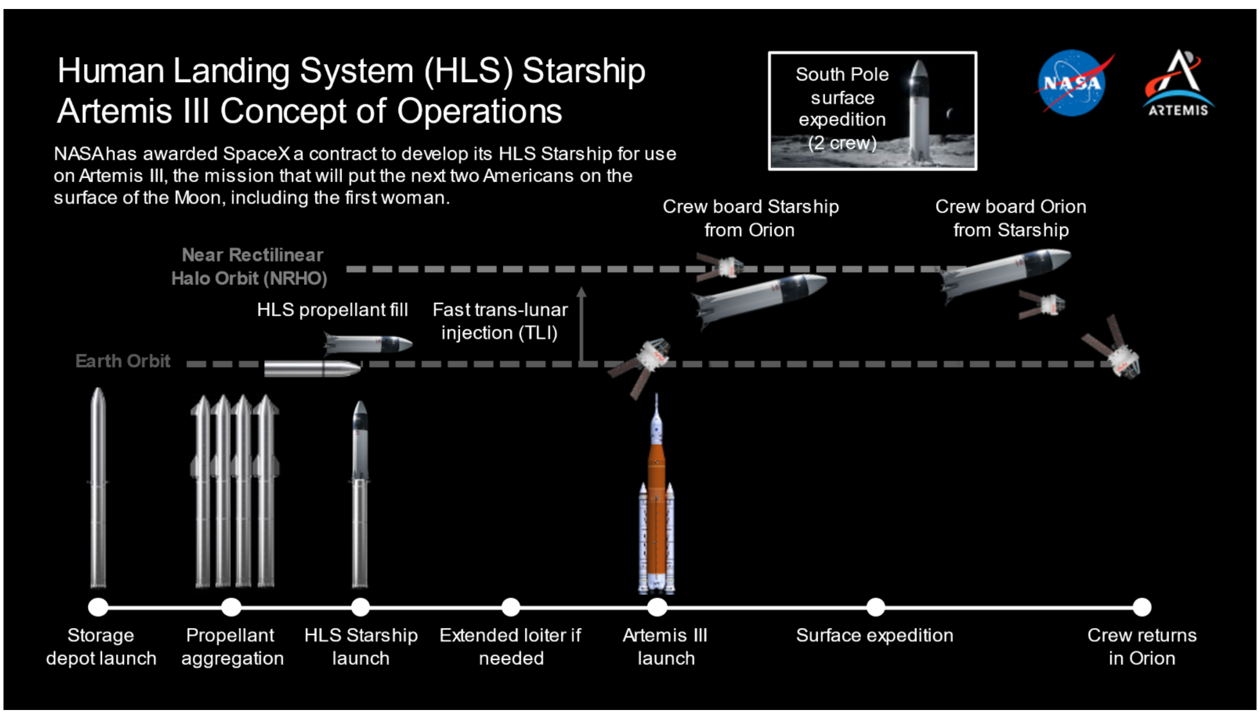

Fig. 4. HLS Artemis III Concept of Operations

HLS Starship with Orion. The unique architecture proposed by SpaceX for landing on the Moon uses one single-stage landing spacecraft. This means that, while several rendezvous and docking maneuvers will be required to load propellant into the HLS Starship before the crewed mission begins, there are no major docking or undocking events required to execute the lander's mission, apart from the rendezvous in NRHO with Orion. Although this single-stage lander concept simplifies the overall crew mission profile by reducing the number of crew-critical docking and undocking procedures (compared with the Apollo lunar module which required successful separation of the Ascent Module from the Descent Module prior to lunar ascent), these maneuvers cannot be eliminated altogether. Notably, the Starship and Orion must execute a successful rendezvous and docking sequence when the crew returns from the lunar surface if they are to return safely to Earth in the Orion capsule. Therefore, significant efforts are currently underway to define the nominal and off-nominal maneuvers and sequences required to support a successful docking. This includes evaluations of the full capabilities of the existing Orion navigation and remote sensing systems and the development of the reciprocal HLS Starship systems.

Other interface definition work is also underway, including refinement and finalization of the Interface Requirements Document (IRD) that spells out not only the physical connections that ensure mechanical compatibility between the spacecraft, but also provisions for resource sharing critical to the extension of Orion's in-space service life. Work has also begun on the development of Interface Control Documents (ICDs) that will define the design solutions to meet the requirements outlined for both sides of this mission-critical interface.

3. Safety and Mission Assurance

The HLS Safety & Mission Assurance (SMA) office is organized to include insight into SpaceX, support for the HLS program, and representation on behalf of the HLS program in cross-program and agency SMA areas. The HLS SMA office is primarily organized by discipline, which includes System Safety, Reliability & Maintainability, Probability Risk Assessment (PRA), Quality Assurance, Software Assurance, Planetary Protection, Crew Survivability, and Government Furnished Equipment Integration. The HLS SMA team includes members from multiple NASA centers and is led by the HLS Chief SMA Officer (CSO).

During the early formulation phase of the HLS program, SMA was focused on ensuring the correct SMA-related requirements were captured as part of the baseline and that the proper planning documents were in place. The HLS CSO partnered with the HLS Chief Engineer to conduct a multi-month process to gain agreements on how the NASA standards and requirements would be implemented for the initial HLS mission. Final decisions were made at an HLS Control Board with Agency Technical Authority participation. HLS SMA also ensured the proper human rating requirements were captured either contractually or in the Program System Requirements Document (PSRD) as they relate to SMA. All these activities culminated in a successful Certification Baseline Review.

Another area of focus for SMA was the development and baseline of planning documents. The primary document is the HLS SMA Plan, which documents all SMA government responsible activities and products in support of mission assurance. SMA is responsible for conducting safety reviews of HLS hazard reports throughout the Design, Development, Test, Evaluation (DDT&E) lifecycle for SpaceX. These process details are captured in the HLS Safety and Engineering Review Panel (HSERP) Charter and HSERP Implementation Plan. Compliance with and the approval process for planetary protection requirements are captured in the HLS Planetary Protection Plan, and mishap planning and communication agreements are documented in the Mishap Preparedness and Contingency Plan (MPCP).

Once the HLS program entered the execution phase, SMA actively began developing certification products and conducting integration activities. The System Safety team baselined the HLS Cross-Program Fault Tree Analysis (FTA). This analysis identifies hazards that may be inherent between HLS and other interfacing Artemis programs. This product was shared with SpaceX to help with development of vehicle hazard reports.

Another area of SMA accomplishment is regarding HSERPs. Multiple HSERPs have been conducted with other Artemis programs and for government furnished equipment toward approving hazard reports. Additionally, HSERP Technical Interchange Meetings (TIM) have been conducted to share lessons learned from different programs and with the Industry Partner toward planning for future hazard report review and approvals.

NASA also has the responsibility to provide the HLS Probability Risk Assessment and Crew Survivability Analysis Report (CSAR). These products support both final design certification and overall Human Rating certification. They mature along the lifecycle at each HLS major milestone and currently have preliminary baselines. The Quality Assurance team developed the HLS Quality Assurance Surveillance Plan, which defines the government surveillance strategy based on areas of highest risk during design and development, production, and operations.

4. Collaboration and Insight

4.1 Collaboration

A novel addition to the HLS procurement approach provides for the ability of the HLS industry provider to tap into the NASA workforce through what is called a collaboration task agreement. Through a collaboration task, the provider can take advantage of NASA's decades of experience in human space flight programs and system development. Working through the HLS Program Office, the provider may reach out to any of the ten NASA field centers to take advantage of their respective areas of expertise, such as propulsion design, cryogenic fluid management analysis, human in the loop test planning, conducting wind tunnel testing, and any host of other technical areas. Collaboration tasks may vary in length; some may last only weeks while others may go on for years.

For the industry provider, collaboration tasks are a mechanism by which they can manage their workforce. In cases where the provider may need a subject matter expert (SME) for only a brief period of time, they can choose to engage a NASA SME to accomplish a short-term task rather than go through a lengthy hiring process for the same short-term need. On the other hand, the provider may choose to engage the NASA SME for longer periods of time to take full advantage of their knowledge and experience through multiple design iterations.

Collaboration tasks are also of great value to NASA. They provide an opportunity for our NASA SMEs to further develop their expertise by engaging more deeply in the design and development of the provider vehicle and the knowledge gained through the collaboration task will be of great benefit to NASA in future programs. While a NASA SME cannot support more than one industry provider by nature of the proprietary architectures proposed for each HLS, NASA also gains a great deal of expertise in the many approaches to lander design and engineering solutions that will benefit future programs.

Collaboration may also be achieved by means of a government task agreement (GTA). GTAs are typically reserved for instances where the provider needs access to unique government facilities such as test stands, vacuum chambers, or other high value or unique assets that may not be commercially available or would be cost prohibitive to build and support a single program. Through a GTA, a provider can gain access to these unique facilities as well as the experts that operate them.

As with collaboration tasks, partnering to make use of these unique facilities is of great value to NASA. By making use of the facilities and SMEs, NASA can gain additional insight into the provider design and grow their experience base. Both of which contribute to making the Agency technically stronger and contributes to the success of the program.

4.2 Insight

While the design, development, test, and integration (DDT&E) of the HLS vehicle is completely the responsibility of the industry provider, the HLS program maintains visibility into the vehicle design through technical insight. The HLS program is committed to implementing risk-based insight where insight resources are strategically applied to minimize risk to certification and mission execution. As the program progresses and the vehicle matures, insight priorities are expected to evolve, and insight plans may be adjusted as necessary to reflect changing or emerging risks.

The HLS program typically limits its insight to review of partner documentation, plans, and processes associated with a particular activity. However, in instances where the HLS program's technical team deems necessary, the insight may be increased to include independent modeling or analysis.

The HLS program strives to perform insight on a non-interference basis wherever possible. And while insight level approvals include some discussion of estimated impact on the provider, provider engagement in insight plan development or approval is not required. During execution, issues with insight or mitigations to minimize provider impact are addressed via ongoing engagement between the SpaceX Insight Coordinator and the HLS program's Lead Systems Engineer.

Collaboration and insight with the SpaceX team and completion of both the uncrewed and crewed demo flight under Option A require a robust exchange of information and insight from both sides now and into the future. The lessons learned from commercial Starship development are directly applicable to the development of the HLS Starship and will help in the progress of NASA's sustainable missions in the future.

5. Sustaining Lunar Development

In the spring of 2022, NASA finalized its acquisition approach for sustaining lunar landers [4] built to an extended set of requirements, applying a three-pronged approach: (1) a new procurement to bring on a second industry provider for sustaining lunar lander development culminating in a crewed demonstration landing; (2) awarding the Option B scope of work to SpaceX's Appendix H contract, thereby asking SpaceX to transform its initial lander capability into one that meets NASA's extended sustaining requirements; and (3) conducting a future procurement for regularly recurring lunar landing services. The HLS program released a draft solicitation for HLS Sustaining Lunar Development shortly after releasing its acquisition approach [5]. The HLS procurement path is depicted in Figure 5.

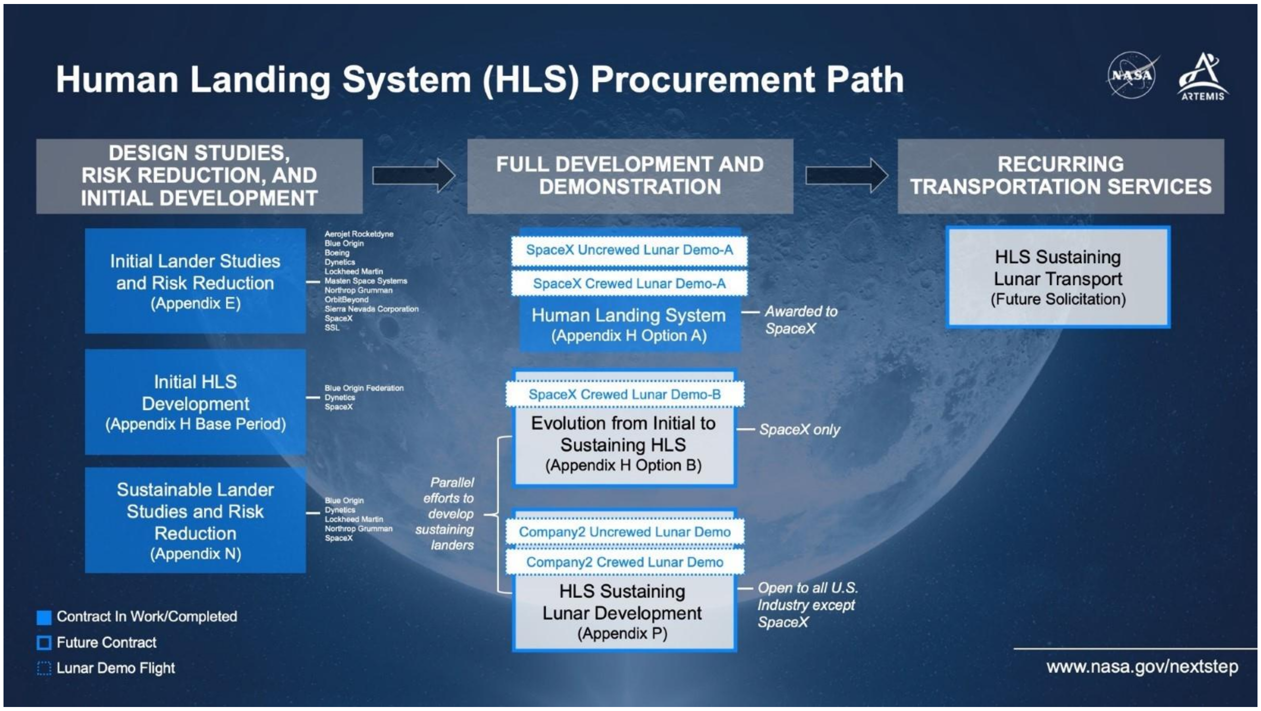

Fig. 5. The HLS Procurement Path

This strategy was implemented to promote competition and support the entry of additional commercial providers into the lunar lander services market, ultimately promoting HLS resiliency. NASA's acquisition plan to achieve two providers is shown in Figure 6.

In the fall of 2022, NASA plans to award SpaceX the Option B contract. As the only Option A provider, SpaceX is also the only company eligible for Option B. The objective for Option B is to develop and demonstrate a lunar lander that meets NASA's sustaining requirements for missions beyond Artemis III. This work will culminate with another crewed demonstration landing.

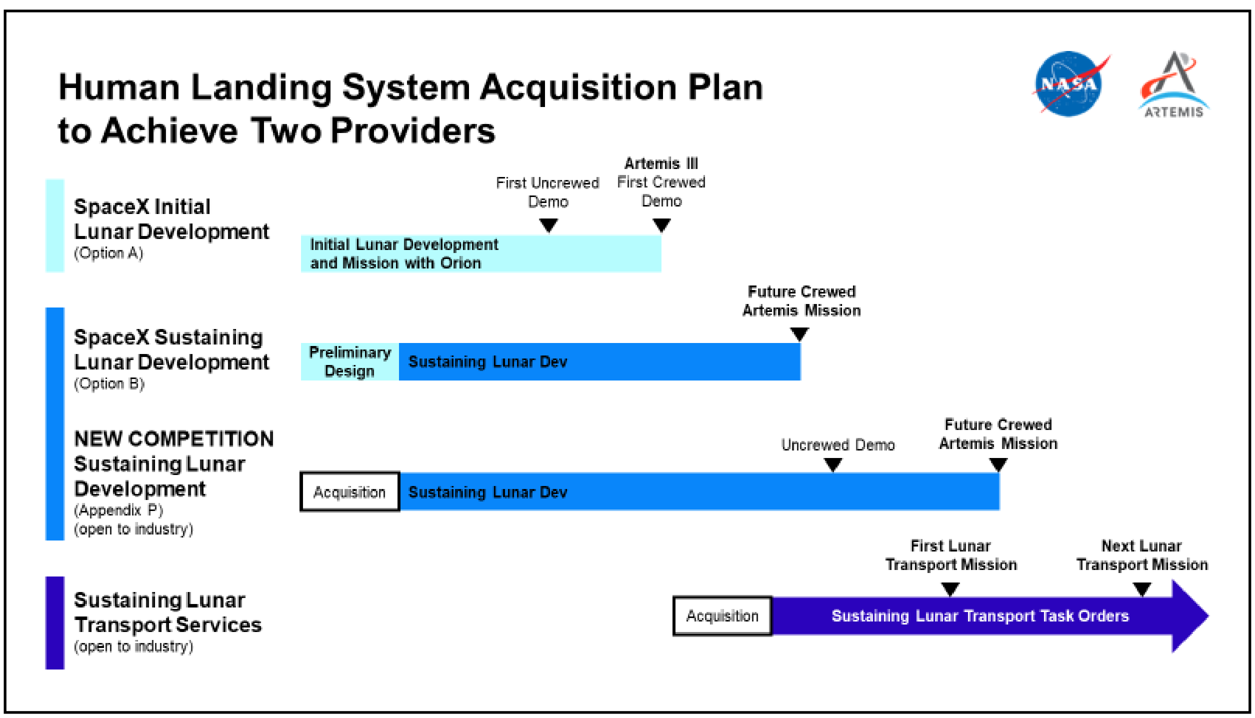

Fig. 6. NASA's acquisition plan to achieve two providers

Concurrent with Option B, NASA is asking industry to compete for a separate procurement under NextSTEP Appendix P, known as Sustaining Lunar Development. This solicitation will be released in the latter part of 2022 and seeks to bring a second entrant to market for the development of a lunar lander in parallel with SpaceX. This effort is meant to maximize NASA's support for competition and provide redundancy in services which will help ensure NASA's ability to transport astronauts to the lunar surface. This strategy bolsters industry readiness and competition for HLS services and promotes a resilient plan for establishing a long-term human presence under Artemis with regular transportation to and from the lunar surface.

6. 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 groundbreaking 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, and through Option A and working closely with SpaceX, the HLS program will facilitate the rapid development and demonstration of the human landing system that will deliver the first woman, and in a later mission, 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 and to being one of many customers purchasing lunar transportation services.

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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