NASA's Initial and Sustained Artemis Human Landing Systems

Lisa Watson-Morgan
NASA-Marshall Space Flight Center
4221 Rideout Road
Huntsville, AL 35811
lisa.a.watson-morgan@nasa.gov

Greg Chavers
NASA-Marshall Space Flight Center
4221 Rideout Road
Huntsville, AL 35811
greg.chavers@nasa.gov

John Connolly
NASA-Johnson Space Center
2101 East NASA Parkway
Houston, TX 77058
john.connolly-1@nasa.gov

Kathryn Crowe
NASA-Marshall Space Flight Center
4221 Rideout Road
Huntsville, AL 35811
kathryn.crowe@nasa.gov

Don Krupp
NASA-Marshall Space Flight Center
4221 Rideout Road
Huntsville, AL 35811
don.krupp@nasa.gov

Laura Means
NASA-Marshall Space Flight Center
4221 Rideout Road
Huntsville, AL 35811
laura.means@nasa.gov

Thomas Percy
NASA-Marshall Space Flight Center
4221 Rideout Road
Huntsville, AL 35811
thomas.k.percy@nasa.gov

Tara Polsgrove
NASA-Marshall Space Flight Center
4221 Rideout Road
Huntsville, AL 35811
tara.polsgrove@nasa.gov

Jason Turpin
NASA-Marshall Space Flight Center
4221 Rideout Road
Huntsville, AL 35811
jason.b.turpin@nasa.gov

***Abstract*—On March 26, 2019, in keeping with President Trump's Space Policy Directive-1, Vice President Pence charged NASA with landing the first woman and the next man on the South Pole of the Moon by 2024, followed by a sustained presence on and around the Moon by 2028. NASA's Human Landing System (HLS) Program is responsible for the final mode of transportation in deep space that will carry humans to and from the surface of the Moon, to be designed and developed by American companies for NASA's Artemis lunar exploration program. This paper examines the approach for Artemis human landing systems for both the initial missions and future sustained missions. While achieving the 2024 goal requires a focus on speed and the use of mature technologies, planning toward sustained operations to and from the lunar surface requires a focus on reliability and reusability. The two approaches, however, are not mutually exclusive, as demonstrated by the HLS prime contractors' integrated lander system proposals.**

On April 30, 2020, NASA announced that Blue Origin of Kent, Washington, Dynetics (a Leidos company) of Huntsville, Alabama, and SpaceX of Hawthorne, California, were the awardees for NASA's Human Landing System contracts under Appendix H of the NextSTEP-2 Broad Agency Announcement. The companies began work in a 10-month base period during which NASA teams worked with the companies to streamline the review of required products and to share the agency's expertise in human spaceflight systems development. Following the base period, NASA will determine which companies will develop the human landers for the initial missions, including the 2024 landing, and which companies will develop landers for future sustained missions toward the end of the decade.

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1. INTRODUCTION

On March 26, 2019, in keeping with President Trump's Space Policy Directive-1 [1], Vice President Pence charged NASA with landing the first woman and the next man on the South Pole of the Moon by 2024, followed by establishing a sustained presence on and around the Moon by 2028. In response to these charges, NASA developed the Artemis program to encompass the agency's lunar exploration efforts. The agency's Human Landing System (HLS) Program is responsible for the final mode of transportation in deep space that will carry humans to and from the surface of the Moon. These human landing systems are being designed and developed by American companies in partnership with NASA for the Artemis lunar exploration program.

Blue Origin of Kent, Washington, Dynetics (a Leidos company) of Huntsville, Alabama, and SpaceX of Hawthorne, California, were the awardees for NASA's Human Landing System contracts under Appendix H of the NextSTEP-2 Broad Agency Announcement [2]. The companies began work in a 10-month base period during which NASA teams worked with the companies to streamline the review of required products and to share the agency's expertise in human spaceflight systems development.

Following the base period, NASA will determine which company or companies will develop the human landers for the initial 2024 mission and which companies will be provided an opportunity to compete for sustaining missions and ultimately human lander services contracts.

To accomplish the goal of developing Human Landing Systems for both Initial and Sustaining Phase missions to the lunar surface, NASA is leveraging the partnership framework from its Commercial Crew Program. In this framework, industry is required to develop an end-to-end integrated Human Landing System that is subsequently delivered to lunar orbit to be checked out and readied for use by the crew. This approach stands in contrast with traditional NASA programs where the government is responsible for procuring individual elements from industry through cost-plus contracts and integrating those elements into a final system. With the Human Landing System Program, NASA seeks to promote the development of a service-based economy where spacecraft are privately owned by U.S. industry, similar to the approach for delivering and returning cargo and crew to the International Space Station. Using competitive service contracts to move crew, cargo, and science to and from the surface of the Moon provides NASA with a more cost-effective approach, allowing for a long-term, sustainable lunar presence. An enduring presence on the lunar surface will serve as the catalyst for a dynamic lunar economy while simultaneously providing a proving ground for future crewed exploration missions to Mars.

This paper examines NASA's approach to providing Artemis Human Landing Systems for both initial and future sustained missions. While achieving the 2024 goal requires a focus on speed and the use of mature technologies, planning toward sustained operations to and from the lunar surface requires a focus on reliability and affordability. As will be revealed, the two approaches are not mutually exclusive but in fact complimentary.

2. MISSION COMPARISON: INITIAL VS. SUSTAINING

Artemis's lunar surface exploration campaign is generally divided into two segments: Initial and Sustaining [3]. The Initial Phase is focused on demonstrating the ability to land the first woman and next man on the surface of the Moon. One of the companies contracted to develop human landing systems will execute the crewed lunar landing demonstration in 2024. These demonstration missions will quickly give way to sustainable lunar exploration, which will begin with the third mission to the surface and feature more capable landers and surface systems. The Sustaining Phase will build on the accomplishments of the Initial Phase, focusing on long-term exploration of the lunar South Pole and demonstration of Mars-forward capabilities.

Mission Objectives

The Human Landing System mission objectives [4] from the Initial Phase will provide the building blocks for those in the Sustaining Phase. In the Initial Phase, objectives are focused on demonstrating the ability to land and work on the surface of the Moon. NASA, leveraging the demonstrated crew flight capability of the Space Launch System and the Orion spacecraft, will land a crew of two astronauts on the lunar South Pole using an industry-developed Artemis Human Landing System (HLS). Living and working out of the HLS, the crew will execute a series of Extra-Vehicular Activities (EVAs) dedicated to diverse science activities and the closure of Strategic Knowledge Gaps, including demonstrating the capabilities of the Exploration Extravehicular Mobility Unit (xEMU) suit. During this period, each HLS contractor selected to field an integrated lander will demonstrate these capabilities, laying the groundwork for more ambitious missions in the future.

For the 2024 mission, the contractor teams have the flexibility to select either Orion or Gateway as their crew staging vehicle in Near Rectilinear Halo Orbit (NRHO). While the Sustaining Phase of lunar exploration will see the crew transferred through Gateway in NRHO, the HLS demonstration flight in 2024 permits direct docking with Orion. Contractors choosing an Orion-only mission profile will dock directly to Orion's active docking port, supporting a lighter and simpler docking system on the lander and simplifying docked operations. However, the contractors will also need to provide Orion consumables, including atmospheric gasses, to extend the operational duration of Orion to meet the needs of a typical lunar mission. Selection of a Gateway-based architecture will require the HLS contractors to determine the best way to dock with a passive docking port, either through the development of a docking adapter or by carrying a heavier and more complex docking system on their lander. However, the Gateway can be leveraged in this mission profile to support the Orion mission duration extension. By offering this flexibility in planning the 2024 mission, NASA allows each HLS contractor to choose the crew staging vehicle that gives their architecture the greatest chance for a successful return to the lunar surface by 2024.

As Artemis transitions into the Sustaining Phase, characteristics such as affordability (i.e., reusability, etc.), sustainability, and an evolutionary path of human exploration will drive mission objectives. The Sustaining Phase will expand U.S. human spaceflight operations at the Moon to support sustained lunar surface activities that likewise demonstrate elements of a Mars-forward architecture. More ambitious lunar surface exploration missions will include the build-up of surface systems such as unpressurized and pressurized rovers and surface habitation elements, ultimately establishing the Artemis Base Camp. This Base Camp will support in-depth investigation and extended duration missions at the lunar South Pole. Additionally, lunar sorties will expand to explore regions beyond the lunar South Pole, extending to a wide range of scientifically interesting sites across the lunar surface. The agency will also leverage a lunar presence to support development of spacecraft, operations, and a body of knowledge about how to live and work in space that will support human exploration of Mars.

The ambitious nature of the Sustaining Phase of lunar surface exploration will drive human landing systems to be more capable. However, the goal of carrying crew to the surface of the Moon regularly necessitates the development of affordable landing system architectures capable of supporting many round-trip flights between orbit and the lunar surface. While affordability and sustainability can manifest themselves in many ways in a landing system design, several key design decisions play prominently in this Phase of exploration. Returning many times to the same surface location using the same flight profile lends itself to the development of reusable surface access systems. By reusing some or all of the elements of a human landing system, costs will be amortized across multiple missions. This reusability attribute will require the development of a logistics chain from Earth to lunar orbit that includes the delivery of propellant, making in-space propellant transfer a key technology of a reusable system. With an established Artemis Base Camp comes the ability to build up infrastructure, including in-situ propellant production to further enable the reuse of landing systems and demonstrate a key component of Mars exploration technology. Another potential manifestation of affordability and sustainability may be the development of low-cost, expendable elements which may leverage rapid, low-cost manufacturing. Regardless of the methods used, a key focus of the Sustaining Phase of lunar surface exploration will be affordably and sustainably expanding human exploration of space.

Mission Requirements: Initial Phase

During the Initial Phase, in order to take the first steps toward enabling humans to live and work on the surface of the Moon, an Artemis Human Landing System carrying the xEMU EVA suits and other mission-enabling logistics will meet the crew in NRHO. The mission requirements and concept (see Figure 1) were created to be goal oriented and architecture agnostic, with a focus on maximizing the vehicle design space for each HLS contractor while developing an evolutionary path to the Sustaining Phase of exploration.

Initial Phase Mission Requirements [4]:

- Transport suits and mission-enabling logistics to NRHO
- Rendezvous with crew staging vehicle (CSV) in NRHO
- Transport two crew, suits, and science equipment to surface for 6.5-day South Pole lunar surface stay
- Enable at least two surface EVAs with a goal of five
- Perform the trip to the lunar surface and back in eight days
- Return samples, suits, and crew to NRHO
- Re-rendezvous with CSV for crew and sample return to Earth
- Extend Orion's total mission duration capability

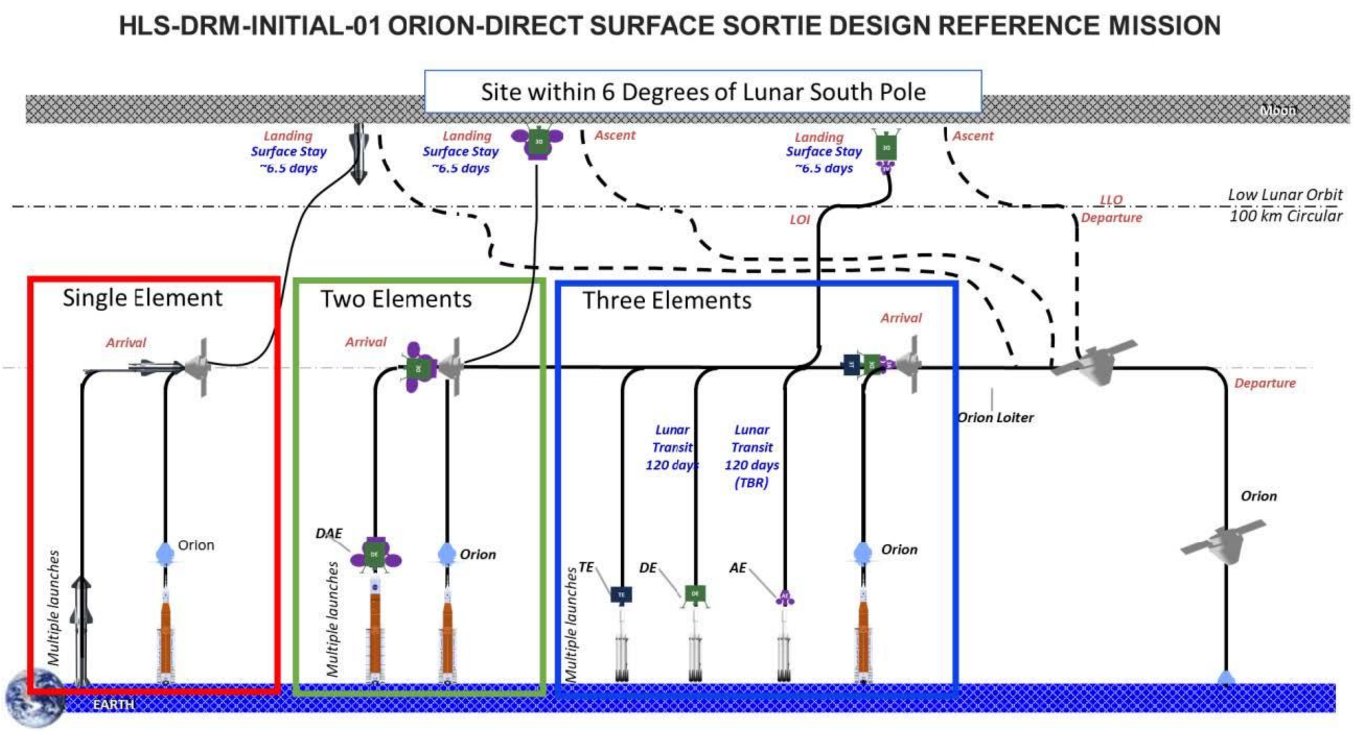

Figure 1. Initial Phase Concept of Operations

The HLS will be launched from Earth to NRHO with suits and mission-enabling logistics, including xEMU suits. The specific profile of the transit to NRHO will be determined by each HLS contractor, but all will have the end goal of having HLS in NRHO ready for crew arrival. Prior to crew launch in Orion onboard an SLS, the HLS will undergo a thorough checkout to make sure that the vehicle is healthy and ready for crew arrival.

Once the checkout is complete, the Artemis crew launches on a fast trajectory and begins their journey to cis-lunar space. The duration of their journey will vary between specific mission dates but will always end with Orion inserting into NRHO and rendezvousing and docking with Gateway or the HLS. Once docking is complete, the sole focus is ensuring that the HLS, suits, and surface equipment are ready for the surface sortie. The HLS will undergo a thorough internal checkout to ensure the cabin is in nominal operating condition before crew ingress. Equipment will be unpacked, checked out, and stowed in surface sortie configuration. The xEMU EVA suits will receive an entire day of checkouts, fitting, and surface sortie preparation by the crew. Lastly, prior to final crew ingress, the HLS will receive a final checkout, similar to a pre-launch countdown.

When the crew and vehicle are ready for the surface sortie, the HLS will undock from the crew staging vehicle and, once a safe distance has been achieved, will perform the NRHO departure burn to begin descent to the lunar surface. During descent transit, the HLS takes a trajectory from NRHO to a circular low lunar orbit (LLO), similar to the low lunar orbits used on Apollo for separating the LEM from the CM, taking approximately half a day. At the end of the transit, the HLS inserts into LLO, where the vehicle will perform navigation state updates and the crew will don suits for final descent. Once all preparations are complete and the HLS has reached the right location in LLO, the HLS will perform a descent orbit initiation or low lunar orbit departure burn that inserts the vehicle on a landing trajectory. After the burn, the HLS coasts for a short period before performing the final descent burn sequence to arrive at the desired landing location within 100 meters of a site of scientific interest.

For the Initial Phase, the focus turns toward surface exploration in the form of EVAs immediately following landing. For the Initial Phase missions, each surface sortie will be the first time the crew uses the industry-developed HLS to perform EVAs on the surface of the Moon. Thus, the objective of highest priority is to ensure proof of surface living and EVA concepts. While the number, duration, and timing of EVAs will depend on each vehicle's capability, Figure 2 shows a typical 6.5-day surface sortie.

The goal for these Initial Phase EVAs is to explore an area up to 2 kilometers around the HLS to enable the collection of a variety of lunar surface samples to be carried back to the crewed staging vehicle on the HLS.

At the end of the surface stay, the crew will ensure the HLS is ready to perform ascent, similar to a pre-launch countdown. At the desired time, the HLS will perform the ascent burn and insert into a trajectory that arrives back at the original low lunar orbit. The vehicle will again perform a series of nav-state updates prior to performing a burn to depart from low lunar orbit and inserting onto a trajectory back to NRHO. This return transit to NRHO, like the initial transit, is a half-day transit and is ended by an NRHO insertion burn.

After arriving in NRHO, the HLS will rendezvous with the crew staging vehicle. If the CSV is Orion, Orion will dock to the HLS. If the CSV is Gateway, the lander will dock to Gateway.

Mission Requirements: Sustaining Phase

For the Sustaining Phase, the mission focus is on leveraging as much as possible of the capability developed in the Initial Phase to provide a lunar transportation service that enables a much broader range of surface living and exploration. This includes using Gateway as the crew staging vehicle for every mission (see Figure 3) and HLS contractors using the Gateway Logistics Service for delivery of suits and mission logistics as needed. Similar to the Initial Phase, Sustaining Phase missions are planned to maximize design flexibility with a focus on exploration goals.

Sustainable Phase Mission Requirements [4]:

- Rendezvous with and dock to Gateway in NRHO
- Transport two crew, suits, and science equipment to South Pole for 6.5-30-day (or more) surface stay depending on available surface systems and logistics
- Transport two crew, suits, and science equipment to non-polar location for <6.5-day surface stay
- Enable five surface EVAs

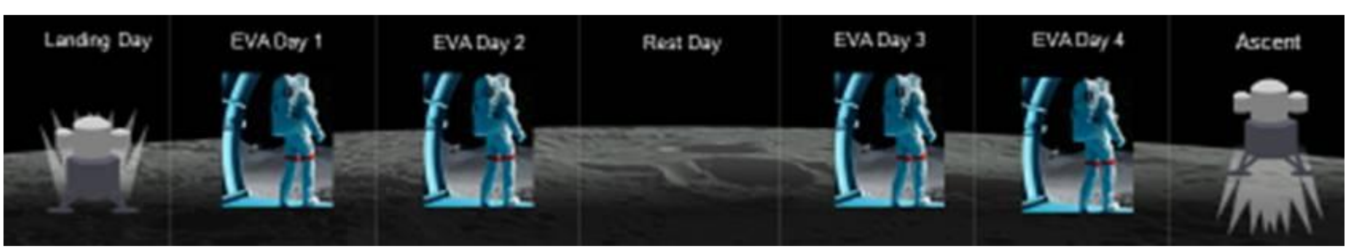

Figure 2. Initial Phase 6.5-day surface sortie

- Withstand the lunar night
- Bring back samples, suits, and crew to NRHO
- Re-rendezvous and dock with Gateway for crew and sample return to Earth

To this end, the HLS Program will provide three types of Sustaining Phase missions: the Polar Surface Sortie, the Lunar Surface Extended Stay, and the Non-Polar Sortie.

The Polar Surface Sortie maintains the ability for two crew to have 6-6.5-day surface stays, with the top-level concept of operations nearly identical to Initial Phase missions. The HLS will have a performance increase above the Initial Phase requirements with the ability to carry more mass to and from the lunar surface. The crew on such a mission could use the 6-6.5 days on the surface to collect more lunar samples, pre-deploy equipment for future missions, perform maintenance tasks on surface equipment, etc.

On a Lunar Surface Extended stay mission, all four Orion crew would travel down to lunar surface in the HLS. The transit profile would be identical to that described in the Initial Phase section. After landing, all four crew would focus on ensuring the suits are ready for the walking transfer over to a surface asset, such as a habitat or Lunar Terrain Vehicle. The crew, alongside the vehicle's automated systems, would then place the HLS into a dormant surface operation mode. Once these preparations are complete, the xEMU-suited crew exit the HLS and walk to the surface asset where they will spend the next four weeks living and working. When the crew are ready to leave the surface, the HLS will receive a signal telling it to begin waking up and transitioning to ascent mode. The xEMU-suited crew will then exit the surface asset to walk back to and ingress into the HLS, which will then ascend back to NRHO in the same way as the Initial Phase missions.

For a Non-Polar Sortie, the general mission profile looks very similar to a Polar Surface Sortie. HLS will rendezvous and dock with Gateway, suits and equipment will be placed in the HLS, then the crew will do a final ingress before the HLS undocks from Gateway. Once at a safe distance, the HLS will perform the NRHO departure burn placing it on a transit to low lunar orbit, passing over the desired non-polar landing spot. The transit from NRHO to this orbit will be much longer than the transit to a polar LLO. Once the HLS has inserted into LLO, the mission profile is very similar to a Polar Surface Sortie with the exception of the surface stay. Since the transit to and from NRHO is longer than that of a Polar Surface Mission, the surface stay for a Non-Polar Sortie will be less than 6-6.5 days, closer to the duration required for a 1-2-EVA surface mission.

Mission Requirements: Comparison

The Initial and Sustaining Phase Concepts of Operations [4] are purposefully similar. The frameworks of missions in both Phases are nearly identical, allowing HLS functionality for both Phases to also be nearly identical. With the exception of the Non-Polar Surface Sortie, the HLS's NRHO operations and transit to and from the surface will be the same, regardless of the number of crew it carries or the duration of the surface stay. Longer-duration surface stay capability is provided by surface assets, which enables continued use of

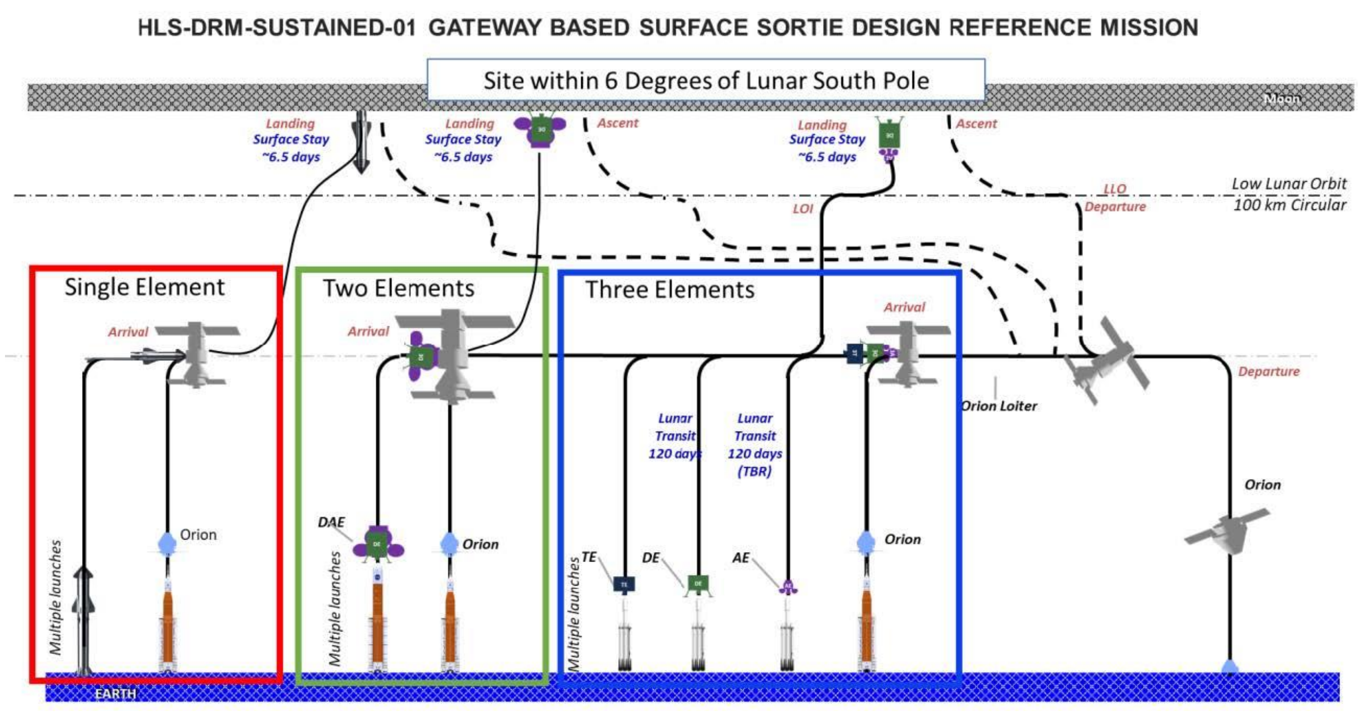

Figure 3. Sustaining Phase Concept of Operations

	Initial Phase	Sustainable Phase: Surface Sortie	Sustainable Phase: Extended Stay	Sustainable Phase: Non-Polar Sortie
Staging Orbit	NRHO	NRHO	NRHO	NRHO
Crew size	2	2	4	2
Transit Profile	0.5-day transit to LLO, followed by loiter and descent	0.5-day transit to LLO, followed by loiter and descent	0.5-day transit to LLO, followed by loiter and descent	
Landing Location	South Pole	South Pole	South Pole	Non-polar region
Total Surface Stay	6-6.5 days	6-6.5 days	30+ days	<6 days
Total Inhabited Surface Stay	6-6.5 days	6-6.5 days	<6-6.5 days	<6 days
Down Mass	870.50 kg	1,595 kg	1,595 kg	870.50 kg
Up Mass	530.5 kg	1,070 kg	1,070 kg	530.5 kg

Figure 4. HLS Design Reference Mission Summary [4]

HLS with minimal changes even when exploration objectives are advanced.

Cargo and Surface System Needs for Sustaining Missions

Sustained lunar surface operations will require the delivery of both fixed and mobile infrastructure needed to expand lunar surface capabilities and establish the Artemis Base Camp. Mobile assets such as unpressurized rovers, pressurized rovers, and offloading and construction equipment will likely be the initial items manifested on cargo landers, followed by power systems, permanent surface habitats, logistics modules, and in-situ resource processing equipment.

The mass and footprint of each surface element will vary, but all will require the capabilities of an uncrewed cargo lander to reach the lunar surface and establish a sustained infrastructure. A small pressurized rover, or Lunar Terrain Vehicle (LTV), will provide early crews with valuable mobility needed to access scientifically diverse sites and

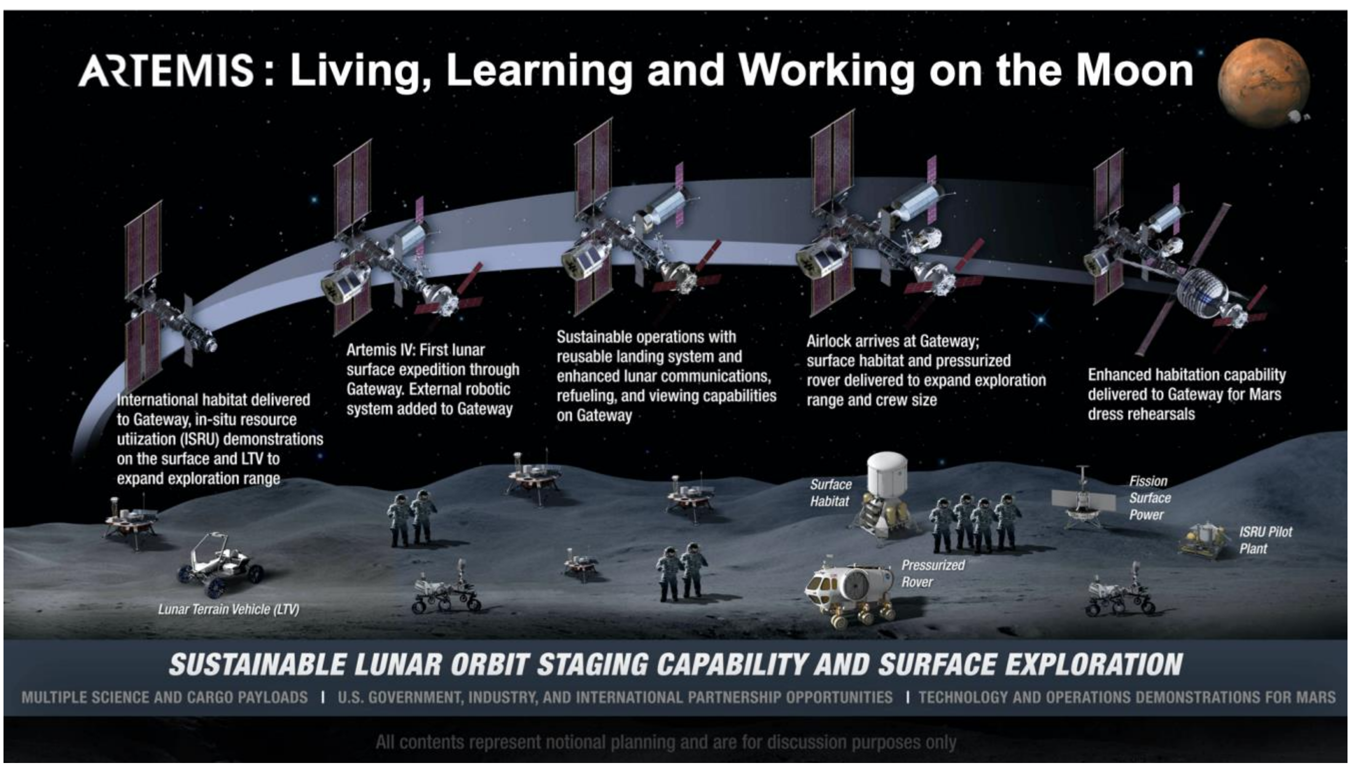

Figure 5. NASA's plan for sustainable lunar orbit staging and surface exploration

explore an extended radius from their landing site. That same LTV can be teleoperated between crewed missions and pre-positioned for use by the subsequent crew. A pressurized rover provides both mobility and surface habitation, extending both range and surface stay duration. Fixed surface habitation will provide a permanent base for future missions with larger crew sizes, expanding over time. Logistics deliveries would be necessary to re-supply pressurized rovers and permanent habitats with the consumables, food, water, oxygen, spares, and supplies needed for the next surface crew, and permanent power systems will be required to supply the growing energy needs of the Base Camp. In-situ resource utilization (ISRU) equipment will then be deployed to utilize available lunar resources and begin to ease the logistics supply chain from Earth by locally producing water, oxygen, and rocket propellants.

Each of the surface elements chosen for the Artemis program will be chosen not only to create a sustained presence on the Moon, but also to demonstrate the hardware systems, technologies, and operations needed for human missions to Mars [5]. A sustained exploration program must continue to reach forward and responsibly explore and use space, and the Artemis Base Camp will provide the foothold for bolder missions into the inner solar system. As illustrated in Figure 5, NASA's exploration plans integrate lunar orbit operations, the lunar surface systems described above, and lunar transportation to sustainably expand human space exploration.

3. PARALLEL DEVELOPMENT APPROACH

HLS's development strategy balances the need to successfully complete the 2024 mission while striving to ensure a competitive environment for human lunar lander services by the end of the decade.

A unique team framework is required for accomplishing this. The HLS Program has established an integrated team of industry and NASA that allows for efficient and effective collaboration. The HLS Program's collaboration model goes above and beyond the traditional government insight and oversight model. For instance, it allows the HLS contractors to integrate and embed NASA personnel and expertise directly within their teams to support design, development, test, and operational activities and it allows the HLS contractors to leverage unique government facilities and equipment to support both development and operations.

Each new phase of HLS development will leverage what was accomplished in the previous phases, with an emphasis on flight testing and uncrewed lunar demonstration missions. At the highest level, this means the Sustaining Phase HLS development will leverage the Initial Phase HLS development. This development will be staggered but will occur in parallel, with the question of how much commonality exists between the systems and how much evolution is required to transform the Initial Phase designs to Sustaining Phase capability.

It appears that the mission capabilities required by a Human Landing System for the Initial Phase 2024 mission and the follow-on Sustaining Phase missions are at odds. Schedule is paramount for the Initial Phase while a regular cadence of missions is the priority of the Sustaining Phase. The 2024 mission in the Initial Phase could leverage approaches that minimize both the required technology development and the overall system capability in order to maximize the probability of maintaining schedule. The Sustaining Phase missions require the development of HLS systems that are both highly capable and affordable by leveraging reusability and in-situ resource utilization.

Trade studies have revealed that approaches that minimize technology and system capability development come with an increased feasibility risk. A design that relies on less efficient systems will necessarily have reduced mass and performance margins to successfully achieve the mission. Thus, a choice must be made between the risk of mission closure and the additional technology development risk associated with unproven but higher-performing systems. If the latter risk is

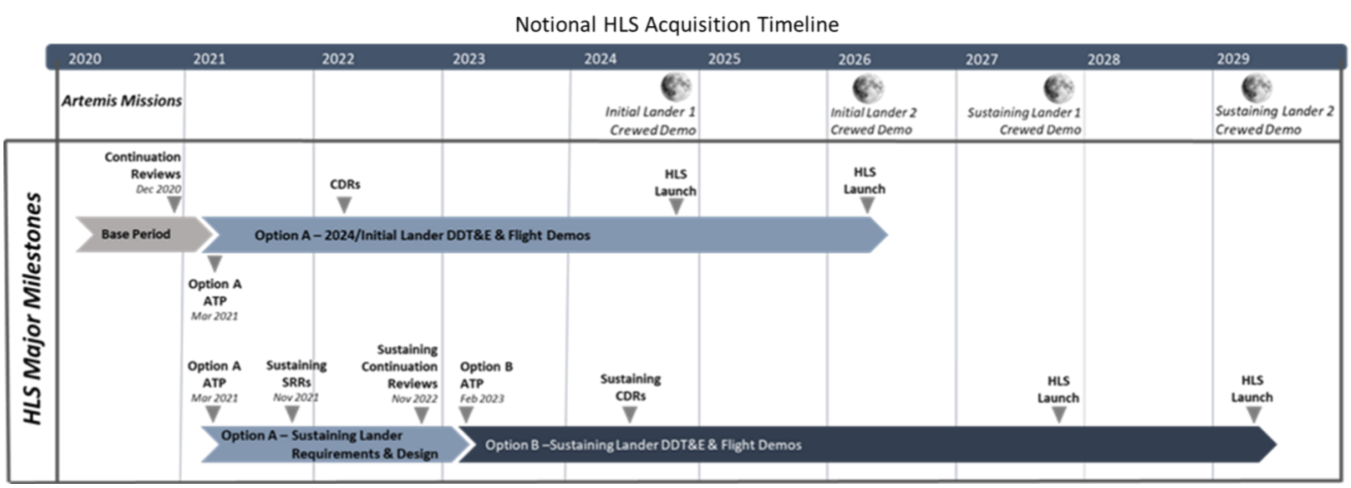

Figure 6. Notional timeline of major HLS acquisition milestones

accepted, it comes with the added benefit of commonality with the requirements for missions in the Sustaining Phase.

In fact, each baseline HLS contractor has made the choice to reduce mission feasibility risk by proposing significant commonality between their initial and sustaining designs. This development is the direct result of the procurement model chosen, where industry sees value in evolving the Initial Phase designs instead of starting over from scratch for the Sustaining Phase.

Acquisition and development of the Artemis Human Landing Systems is planned to occur across four distinct contract phases: 1) Base Period, 2) Option A – Initial Phase, 3) Option B – Sustaining Phase, and 4) Human Lunar Landing Service Contracts [4]. The Base Period is focused on maturing each HLS contractor's design to a point at which a selection can be made for Option A. Option A is primarily focused on the 2024 Initial Phase mission, however it does include some sustaining-specific mission content (see Figure 6). The scope of Option A includes both the design, development, testing, and evaluation (DDT&E) of the HLS as well as the Initial Phase 2024 mission. Option B includes any remaining DDT&E required to evolve the Initial Phase HLS variants to be Sustaining Phase mission-capable and may include up to two demonstration missions as well. Multiple decision gates are built into the HLS development approach that provide opportunities to add missions as part of the Option A and Option B frameworks and to ultimately compete and award human lunar lander services contracts.

4. HLS Systems Overview

The three companies awarded HLS contracts in May 2020 offered three distinct landing system and mission designs, which will drive a broader range of technology development and, ultimately, more sustainability for lunar surface access [6]. Due to the proprietary nature of the ongoing HLS procurement, limited information is available to be shared publicly on each of the three HLS contractors' systems. What follows is a brief overview of each Base Period proposal based on publicly available information as of April 30, 2020.

Blue Federation

Blue Origin is the prime contractor for the Blue Federation team that includes Lockheed Martin, Northrop Grumman, and Draper. Their Integrated Lander Vehicle (ILV) is a three-stage lander that harnesses the proven spaceflight heritage of each team.

Blue Origin will build the descent element which is powered by BE-7 cryogenic engines three years in private development, with cryogenic technologies now under NASA Tipping Point support. Lockheed will build the ascent element that includes the crew cabin, which will have significant commonality with Orion. Northrop Grumman will build the transfer element based largely on its Cygnus cargo module that services the International Space Station. Northrop Grumman is also leading development of a future refueling element for a Sustaining Phase HLS demonstration. Draper will provide the guidance, navigation and control, avionics, and software systems that draw largely on similar systems the company has developed for NASA.

In their proposal, the Blue Origin-led team outlines a plan in which the ILV can dock with either Orion or Gateway to await crew arrival. The team's HLS can be launched individually on commercial rockets or combined to launch on NASA's Space Launch System. [6]

Dynetics

Dynetics is leading a robust team with more than 25 subcontractors specializing in both the larger elements and the smaller system-level components of the Dynetics Human Landing System. The large team capitalizes on Dynetics' experience as an integrator on military and defense contracts with large subcontractor teams.

The Dynetics Human Landing System concept includes a single element providing the ascent and descent capabilities, with multiple modular propellant vehicles prepositioned to fuel the engines at different points in the mission. The crew cabin sits low to the surface, enabling a short climb for astronauts entering, exiting, or transporting tools and samples. The DHLS supports both docking with Orion and with Gateway, getting a fuel top-off before descending to the surface. After the surface expedition, the entire vehicle will return for crew transfer back to Orion. The Dynetics Human Landing System is rocket-agnostic, capable of launching on a number of commercial rockets. [6]

SpaceX

SpaceX's Starship is a fully reusable launch and landing system designed for travel to the Moon, Mars, and other destinations. The system leans on the company's tested Raptor engines and flight heritage of the Falcon and Dragon vehicles. Starship includes a spacious cabin and two airlocks for astronaut moonwalks.

Several Starships serve distinct purposes in enabling human landing missions, each based on the common Starship design. A propellant storage Starship will park in low-Earth orbit to be supplied by tanker Starships. The human-rated Starship will launch to the storage unit in Earth orbit, fuel up, and continue to lunar orbit.

SpaceX's Super Heavy rocket booster, which is also powered by Raptor and fully reusable, will launch Starship from Earth. Starship is capable of transporting crew between Orion or Gateway and the lunar surface. [6]

5. Current Status of Development

As previously illustrated, the current HLS development efforts incorporate many Sustaining Phase attributes within their Initial Phase incarnation. This approach is deemed positive, as long as those attributes do not detract from the 2024 Initial Phase mission success. However, this approach does make it challenging to clearly delineate between Initial Phase development efforts and Sustaining Phase development efforts as they are intertwined by design. The following provides a snapshot of development progress for both the Initial and Sustaining Phase variants with some liberties taken relative to where that line is drawn.

Initial Phase

After Base Period awards were made in April 2020, NASA and each HLS partner spent ten months working toward Certification Baseline Reviews (CBR) in August 2020. The primary purpose of the CBRs was to adjudicate design, construction, safety, and health and medical standards for each proposed landing system. During this time, each HLS partner performed risk reduction activities—including early testing of low-Technology Readiness Level (TRL) items—and developed baseline schedules and management plans for contract execution and human spaceflight certification.

The HLS Program and the three HLS partners are currently, as of October 2020, working toward a Continuation Review (CR) program milestone in December 2020 that will incorporate additional insight data based on updates from the CBRs. The expected closeout of the Base Period is the end of February 2021 with matured HLS designs followed by the award of Option A contracts.

Having received Option A proposals in December 2020, NASA plans to award contracts after the Base Period ends in February 2021, providing a seamless transition to the next phase of HLS development that ultimately culminates in crewed demonstration missions to the lunar surface beginning with the Artemis III mission in 2024.

Sustaining Phase

The scope of the current HLS Base Period contract includes risk-reduction design work specific to the Sustaining Phase HLS variant. This work is above and beyond the conceptual and preliminary design work that has been completed for the Initial Phase HLS variant. Given the commonality between the two, most major subsystems are moving toward a preliminary design level of maturity and directly benefit from the work completed for the Initial Phase missions. After Option A is awarded, the HLS Sustaining Phase requirements will be refined and baselined, and the development of the evolved landing systems will begin.

In parallel, Sustaining Phase Artemis mission manifest and requirements are being refined and iterated across mission elements and will be used to finalize the Sustaining Phase HLS requirement set. As mission manifest and mission requirements are solidified, so too will be the supporting surface system requirements that will be leveraged to support longer-duration, four-crew missions to the lunar surface. Several required surface systems, including a pressurized rover and surface habitat, are large, and will require large cargo lander capability. In anticipation of the need to land such large cargo, the HLS Program is performing initial studies along with Initial and Sustaining Phase development efforts that will add to the foundation for developing a large cargo lander. It is expected that NASA's Space Launch System (SLS) will be available during the Sustaining Phase to deliver additional infrastructure, such as depots to NRHO or large lunar elements needed for Sustaining Phase requirements.

6. SUMMARY

With the announcement of three contract awards in April 2020, NASA and its HLS contractors began work on the Initial Phase of the Artemis lunar surface exploration campaign focused on demonstrating the ability to land the first woman and next man on the surface of the Moon in 2024. During the 10-month Base Period contracts, NASA teams worked with each contractor to finalize system requirements, streamline the review of required products, and share the agency's expertise in human spaceflight systems development. At the end of the Base Period contracts, NASA will determine which company will develop the landing system for the 2024 mission.

While the HLS Program's phased approach for developing and demonstrating the capabilities to land humans on the lunar surface builds on its approach used for the Commercial Crew Program, it stands in contrast with more traditional NASA programs. Each new phase of HLS development will leverage what was accomplished in the previous phases, with an emphasis on flight testing and uncrewed lunar demonstration missions.

With the Human Landing System Program, NASA wants to develop a U.S. industry-owned human landing service capability that can ultimately be acquired by the agency through competitive service contracts, similar to the approach for delivering and returning cargo and crew to the International Space Station. By using competitive service contracts to move crew, cargo, and science to and from the surface of the Moon, NASA is enabling a long-term, sustainable lunar presence. This sustainable lunar presence will open the door for a practical lunar economy and provide an exploration proving ground at the lunar South Pole with the ability to demonstrate the hardware systems, technologies, and operations needed to press forward with future human exploration missions to Mars.

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BIOGRAPHY

Dr. Lisa Watson-Morgan *is the Human Landing System program manager at NASA's Marshall Spaceflight Center. In her previous roles as Deputy Director of Marshall's Engineering Directorate, she was jointly responsible for the Center's largest organization, comprised of more than 2,000 civil service and contractor personnel, leading the design, testing, evaluation, and operation of flight hardware and software associated with space transportation, spacecraft systems, science instruments, and payloads in development. Since her appointment to the Senior Executive Service in 2013, she has served as Manager, MSFC Chief Engineer's Office; Director, Spacecraft and Vehicle Systems Department; and Associate Director of Operations for the Engineering Directorate. Dr. Watson-Morgan graduated from the University of Alabama in 1991 with a bachelor's degree in Industrial Engineering. She received a master's degree in Industrial and Systems Engineering in 1994 and a doctorate in Engineering Management in 2008, both from the University of Alabama in Huntsville.*

Dr. Greg Chavers *is the Deputy Program Manager for NASA's Human Landing System Program Office. Prior to serving in formulation roles at NASA Headquarters, Greg was the Project Manager of the HEOMD/AES Landers Technology project, which included the Lunar Cargo Transportation and Landing by Soft Touchdown (Lunar CATALYST). Dr. Chavers was engineering lead for the Robotic Lunar Lander Development Project from 2011 to 2012. From 2008 to 2010, Dr. Chavers was the lead systems engineer for the International Lunar Network (ILN) lander where he led the development of the Mighty Eagle terrestrial demonstrator. Dr. Chavers holds a M.S. and Ph.D. in Physics from the University of Alabama in Huntsville and a B.S in Aerospace Engineering from Auburn University.*

Mr. John Connolly *is a member of NASA's Human Landing System Program team, planning the return of astronaut explorers to the moon. His 33 year of NASA expertise includes lunar lander design, lunar surface systems, and human Mars mission planning. Connolly has held positions as NASA's Lunar Surface Systems lead, Human Mars Study Team lead, Altair Lunar Lander Deputy Project Manager, Special Assistant to JSC's Astronaut Office, and Chief Exploration Scientist. Mr. Connolly's NASA career has been devoted to defining future systems that will send human crews beyond Low Earth Orbit, return them to the moon, and lead them to Mars and beyond.*

Ms. Kathryn Crowe *is the Human Landing System Deputy Lead for Integrated Performance, responsible for developing the crewed human lander and the Lunar Surface Sortie for sustained return of humans to the lunar surface. Previously, she has served as the co-Lead Systems Engineer on the VIPER (Volatiles Investigating Polar Exploration Rover) Lander. Ms. Crowe also spent several years working on the Space Launch System (SLS) where she led multiple SLS Block 1B architecture trade studies, took lead on major task teams related to cross program integration, and helped resolve multi-disciplinary vehicle design issues. She also served as the SLS Liquid Engines Office Liaison to Stennis Space Center for the initial RS25 Hotfire Test Series and to Aeroject Rocketdyne for RS25 Production Restart. Early in her career, Kathryn served as a Propulsion Test Engineer, where she acted as the Lead Test Engineer on several testing projects. Before coming to NASA, Kathryn served in the U.S. Air Force as an Arabic Cryptologic Linguist and Basic Arabic Language Instructor at the Defense Language Institute (DLI). She has an M.S. in Systems Engineering and a B.S. in Aerospace Engineering from the University of Alabama at Huntsville, and A.A. in Arabic* *from DLI.*

Ms. Laura Means *is a member of the strategic communications team for the Human Landing System Program at NASA's Marshall Space Flight Center in Huntsville, Alabama. A contractor with Media Fusion, LLC, Ms. Means has been with NASA since August 2019. She previously served as the Communications Manager for the Office of the Vice President of Government and Community Relations at the Georgia Institute of Technology in Atlanta, Georgia from 2014-2019. A Georgia native, Ms. Means received a Bachelor of Arts in Communication from Berry College and a Master of Arts in Integrated Global Communication from Kennesaw State University.*

Dr. Tom Percy *is the Integrated Performance Lead for the Human Lander System at Marshall Space Flight Center. Dr. Percy has supported NASA's human and robotic space exploration programs for over 17 years in the areas of advanced propulsion and mission architecture analysis. Dr. Percy's focus areas include human exploration spacecraft and mission concept development, technology assessment, trajectory analysis and advanced propulsion systems. Dr. Percy holds a Bachelor of Science in Mechanical Engineering from Rochester Institute of Technology, a Master of Science in Aerospace Engineering from Georgia Institute of Technology, and Doctorate in Aerospace Systems Engineering at the University of Alabama in Huntsville.*

Mrs. Tara Polsgrove *is the Lead System Engineer with the Human Landing System Program Office at NASA's Marshall Space Flight Center. She is currently focused on the vehicle designs, system engineering, and programmatic assessments for the future human missions to the Moon and Mars, particularly the lander and ascent vehicle for human missions. She has been with NASA since 2000 and has a background in interplanetary trajectory optimization and mission analysis. Ms. Polsgrove has a Bachelor of Science in Aerospace Engineering from the Georgia Institute of Technology and a Master of Science in Engineering with a Systems Engineering focus form the University of Alabama in Huntsville.*

Mr. Jason Turpin *is the Assistant Program Manager - Sustaining for the Human Landing Systems (HLS) Program. He is currently focused on developing HLS's sustaining mission capability. He served for 5 years as manager of Marshall Space Flight Center's Liquid Engine Systems Branch and joined NASA in 1999. His background is liquid propulsion systems including reaction control systems, main propulsion systems, pressure fed liquid engines, and turbopump fed liquid engines. Mr. Turpin has a Bachelor of Science in Mechanical Engineering from Christian Brothers University.*