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Update on NASA's Human Landing System (HLS) Program: Public-Private Partnership Advancing Artemis Sustainable Lunar Exploration

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Abstract

NASA's Human Landing System (HLS) program leads the development of the landers that will land the next astronauts – as well as large cargo – on the Moon under the Artemis campaign. Based out of NASA's Marshall Space Flight Center in Huntsville, Ala., the HLS program marries the extensive human spaceflight expertise of NASA with the speed and innovation of industry to develop key technologies needed for mission success. The HLS program exercises critical insight into providers' designs and coordinates engineering collaboration work to advance lander development. In addition to the development of landers for Artemis crew, HLS providers SpaceX (on contract for Artemis III and IV) and Blue Origin (on contract for Artemis V), the HLS program has given both companies authority to proceed on preliminary development of variants of their crew landers that can deliver large cargo to the lunar surface. Expected to share significant design and systems commonality with the human-class landers, the large cargo landers from SpaceX and Blue Origin will be capable of delivering 12-15 metric tons (t) to the Moon. The HLS program will continue to provide risk-based insight into the designs, systems, testing, processes, and production and launch facilities of both providers as they work toward Critical Design Review (CDR). In addition to risk-based insight activities, NASA plays a key role in lander development by providing engineering expertise and unique testing capabilities to the commercial companies through Collaborations and Government Task Agreements (GTAs). With this development approach, the HLS program harnesses the speed and innovation of American industry, while controlling costs. This partnership, however, relies on NASA providing key engineering insight and collaboration with industry in areas they may not have experience or skills. This paper will review progress the HLS program and its providers made during the past year and look ahead to significant developments leading up to Artemis III, the first human lunar landing of the 21st century. **Keywords:** NASA, Human Landing System, Artemis, Artemis III, Artemis IV, Artemis V, large lunar cargo landers

Acronyms/Abbreviations

Air Force Research Lab (AFRL); Axiom Extravehicular Mobility Unit (AxEMU); Black Point-1 (BP-1); Canadian Space Agency (CSA); Certification Baseline Review (CBR); Commercial Lunar Payload Services (CLPS); computational fluid dynamics (CFD); Concept of Operations (ConOps); Critical Design Review (CDR); cryogenic fluid management (CFM); Design Certification Review (DCR); Environmental Control & Life Systems (ECLSS); Exploration Ground Systems (EGS); Exploration Systems Development Mission Directorate (ESDMD); Extra-Vehicular Activity (EVA); Government Task Agreement (GTA); Guidance Navigation & Control (GN&C); Hub for Innovative Thermal Technology Maturation and Prototyping (HI-TTeMP); Human Landing System (HLS); Independent Verification and Validation (IV&V); Japan Aerospace Exploration Agency (JAXA); Liquid Oxygen (LOX); Lunar Module (LM); Lunar Orbit Checkout Review (LOCR); metric tons (t); micro-meteoroid orbital debris (MMOD); Near-Rectilinear Halo Orbit (NRHO); Neutral Buoyancy Lab (NBL); Low Earth Orbit (LEO); methane (CH4); National Aeronautics and Space Administration (NASA); Plume-Surface Interaction (PSI); Preliminary Design Review (PDR); Probabilistic Risk Assessment (PRA); reaction control system (RCS); Safety & Mission Assurance (S&MA); Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS); Space Launch System (SLS); thermal protection system (TPS); trans-lunar injection (TLI).

1. Introduction to Artemis

Artemis, NASA’s human spaceflight campaign to return astronauts to the Moon with an infrastructure to support a sustained presence in deep space, will lay the foundations for human missions to Mars. NASA’s Human Landing System (HLS) program is managing the development of commercially owned lunar landers for Artemis demonstration missions beginning with Artemis III – the first scheduled human landing since Apollo 17 in 1972. The HLS program has contracted with SpaceX to carry astronauts to and from the lunar surface for Artemis III and Artemis IV using an HLS version of its Starship launch vehicle – a second stage that launches on a Super Heavy first-stage booster. For Artemis V, Blue Origin is contracted to carry astronauts to and from the lunar surface using its Blue Moon MK2 lunar lander.

The Artemis III lander is being built to an initial set of requirements to enable a landing in the near term, while the Artemis IV and Artemis V landers are being designed to a more stringent, robust requirement set to facilitate establishment of a sustainable lunar architecture. Although lander design is left to the commercial providers, the HLS program has insight into designs, tests, and production of the vehicles and associated spacecraft and infrastructure. Insight activities focus on areas where the HLS program determines there is risk; insight activities ensure HLS engineers understand provider designs to inform risk analysis.

Figure 1. Artemis I, an uncrewed flight test of NASA's Space Launch System (SLS) super heavy-lift launch vehicle, Orion spacecraft, and Exploration Ground Systems (EGS) at Kennedy Space Center, lifted off on November 22, 2023.

In addition to insight, the program also coordinates Collaborations between various NASA engineering discipline experts join the provider limited time periods to support a particular area of technology development. Government Task Agreements (GTAs) are another avenue for government-industry knowledge-sharing. Providers can pay NASA for the use of specialized government facilities, including many test facilities, to access unique test and analysis capabilities. Through Collaborations and GTAs, commercial providers are utilizing NASA’s significant engineering expertise, skills, history, and specialized facilities to advance technology readiness for the Artemis missions.

2. Early Demonstration Flights: Artemis I and II

Each Artemis mission builds on lessons learned from previous missions and brings increasing challenges and complexity. In addition, each Artemis mission brings online new assets for deep space exploration, often in partnership with private industry, international space agencies, and/or academia.

First in the Artemis campaign was the uncrewed Artemis I mission that launched November 22, 2022, from NASA's Kennedy Space Center in Florida (see Figure 1). The three-week flight, with the new Orion spacecraft for crew splashing down on December 11, 2022, enabled NASA's Exploration Systems Development Mission Directorate (ESDMD) to rigorously exercise and check out three new assets for deep space exploration: a new super heavy-lift launch vehicle, the Space Launch System (SLS), the Orion spacecraft, and Exploration Ground Systems (EGS), which provides hardware integration, ground processing, launch, and recovery capabilities. Artemis I was NASA's first flight of a crew-capable spacecraft to deep space since Apollo; the test flight met all objectives and provided many lessons learned.

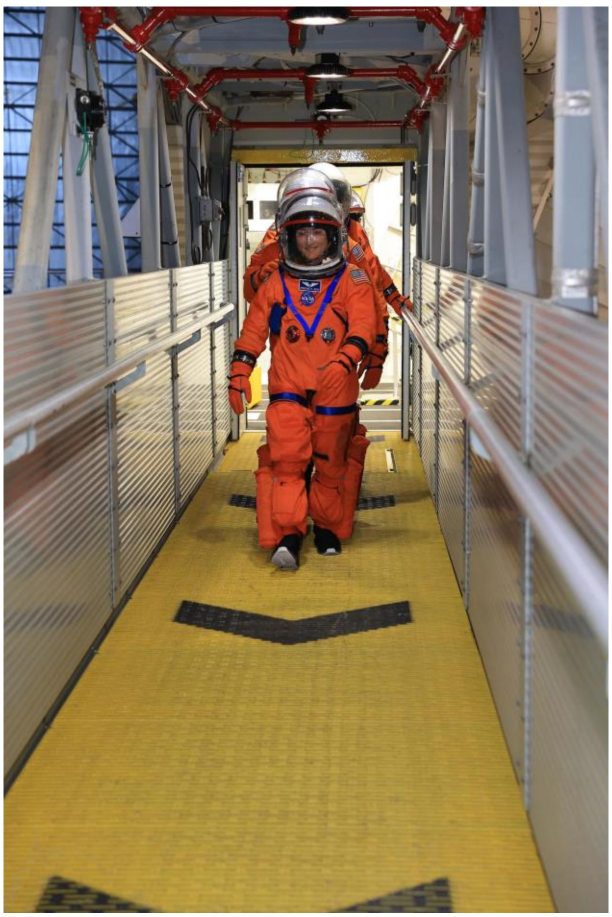

Figure 2. NASA astronaut and Artemis II mission specialist Christina Koch and the other Artemis II crew members transverse the Mobile Launcher's crew access arm while practicing launch day operations in August 2025 in the Vehicle Assembly Building at NASA's Kennedy Space Center.

EGS is currently integrating elements of the Artemis II stack in Kennedy's Vehicle Assembly Building. The Artemis II test flight is scheduled to launch in spring 2026 and will be the first crewed flight beyond LEO since Apollo 17. The four crew members – NASA astronauts Commander Reid Wiseman, Pilot Victor Glover, Mission Specialist Christina Koch; and Canadian Space Agency astronaut and Mission Specialist Jeremy Hanson – are training currently in the Orion spacecraft and for launch-day procedures at Kennedy (see Figure 2). As part of Artemis II, prior to trans-lunar injection (TLI), the crew will perform proximity operations in Earth orbit to test Orion's maneuverability and handling capabilities. The Artemis II mission will be a 10-day powered lunar flyby mission, similar to the Apollo 8 flight.

3. Role of HLS program in Artemis

Beginning with Artemis III, NASA's HLS program will provide the landers that will carry crew to the lunar surface, provide living quarters for crew when they're not conducting extra-vehicular activities (EVAs), and return to them to lunar orbit for the trip home in Orion. In addition, the capability to land large cargo on the Moon and Mars is also in development, scheduled to be available no sooner than Artemis VII (see Section 6).

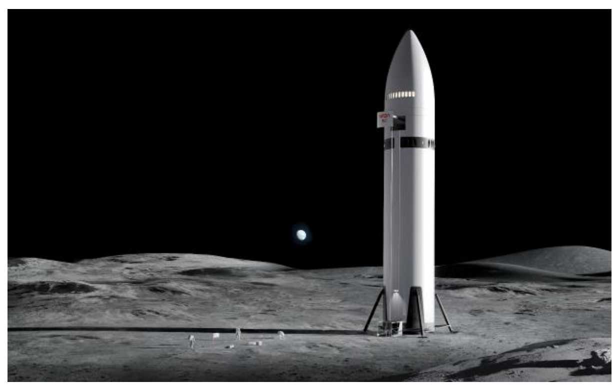

Figure 3. SpaceX is contracted to provide Starship HLS lunar lander capable of supporting two crew members for a 6.5-day surface expedition during Artemis III. (Image credit: SpaceX)

For Artemis III, SpaceX is under contract to provide a lunar lander version of its commercial Starship spacecraft, called the SpaceX Starship HLS (see Figure 3). The Artemis III Starship HLS will receive two crew members from Orion in NRHO and carry them to the lunar surface for the exploration mission (two crew members will remain in Orion in NRHO). The two crew members will stay on the lunar surface about 6.5 days (one NRHO period), with the HLS serving as living quarters for crew when they're not conducting EVAs. At the conclusion of the surface expedition, the Starship HLS will return the two astronauts to NRHO, where it will dock with Orion and the crew will transfer back to Orion. The four-member crew will return to Earth in the Orion spacecraft.

For Artemis IV and Artemis V, NASA's requirement set is more robust, including more mass to the surface and the capability to support longer surface expeditions. SpaceX is also contracted to provide the lunar landing for the Artemis IV, built to the more stringent requirements.

For Artemis V, the HLS program will bring a second provider – Blue Origin – online. Blue Origin is working on its Blue Moon MK2 lander for Artemis V, which meet the same set of extended requirements for a sustainable exploration architecture (see Figure 4). A desire for dissimilar redundancy among Artemis HLS providers was a driving factor in having two lunar landers in development.

Figure 4. Blue Origin is developing the Blue Moon MK2 lunar lander for Artemis V. (Image credit: Blue Origin)

Safety remains the key tenet of NASA's human spaceflight enterprise, including the HLS program. Engineers and safety specialists from NASA's Safety & Mission Assurance (S&MA) organization participate in both SpaceX and Blue Origin insight activities providing expertise, insight, and oversight of:

- Human rating requirements
- Hazard analysis development and risk characterization
- Probabilistic Risk Assessment (PRA) and risk drivers
- Independent Verification and Validation (IV&V) of software

Collaborations and GTAs. In addition to integrating a safety focus into engineering designs, manufacturing, testing, and launch procedures, the HLS program also provides technical expertise to its commercial providers to mature technology and facilitate testing. Agreements known as Collaborations allow SpaceX and Blue Origin to request and utilize NASA engineering experts in areas where they may lack skills, knowledge, or expertise. Companies can also request engineering support or Collaborations during surge activities to help meet schedule requirements. Each provider can request up to 80 equivalent personnel for collaborations each fiscal year. The HLS program coordinates and tracks the Collaborations, matching requested engineering and technical expertise across nearly all NASA centers with the provider's need. Deliverables from Collaborations typically include, but are not limited to:

- Presentations and reports
- Historical studies
- Testing setups, procedures, and matrices
- Test results
- Analysis and simulation data
- Software builds
- Recommendations for follow-up work
- Technical Interchange Meetings (TIMs)

An intentional component of the HLS development contracts, Collaborations have been extremely successful and have utilized NASA engineering expertise and facilities across the agency. The are generally established for an agreed-upon time frame, but often are extended or expanded in scope. The HLS program regularly manages Collaborations that are ending, beginning, or being extended. Collaborations between NASA and the HLS commercial providers have included work in areas such as:

- Cryogenic valve development for long-duration missions
- Computational materials science
- Cryogenic fluid management (CFM)
- Thermal protection system (TPS) design, testing, and analysis

In the area of CFM, engineers at Marshall Space Flight Center and other NASA centers are helping assess tank fluid dynamics during key mission phases. NASA engineers have developed fluid and thermal models, providing pressure recommendations during mission phases and help providers use test data to anchor models (see Figure 5). NASA engineers are developing advanced computational fluid dynamics (CFD) models for slosh under varying conditions and are providing recommendations for design parameters, such as ullage volume, tank shape, etc.

Because large-scale, on-orbit cryogenic propellant transfers are needed to ensure the Artemis lunar landers in development from both providers have adequate payload capacity and delta-v for loitering, docking, landing, and ascent maneuvers, CFM has been and is expected to remain a key area for collaboration between NASA and its commercial providers.

Another collaborative effort between providers and NASA Marshall engineers in support of CFM has been development of low-leakage cryogenic valves for long-duration missions. Marshall engineers are collaborating with providers on hardware anomaly resolutions, creating detailed design guidance, materials selection, manufacturing and fabrication planning, and testing.

Figure 5. NASA Marshall's Hub for Innovative Thermal Technology Maturation and Prototyping (HI-TTeMP) laboratory provides the resources and tools for an early, quick-check thermal evaluation of materials for deep space missions.

NASA Marshall has also provided stress analysis on components such as heat exchangers, tubes, brackets, Environment Control Life Support Systems (ECLSS) structures, and more.

Through Collaborations, commercial providers are taking advantage of experienced engineers who design, set up, test, and help analyze test results. These engineers often provide suggestions for follow-up work or even design considerations – early enough in the design process to incorporate changes help mitigate costly downstream changes. Collaborations often include significant exchange of technical information, with commercial providers benefiting from NASA’s extensive flight history.

GTAs. Another avenue for commercial companies to take advantage of NASA’s extensive capabilities and specialized facilities comes through GTAs. These agreements enable commercial providers to access unique government assets and resources, such as test facilities, launch support, or manufacturing.

One example of a GTA is wind tunnel testing in the unitary wind tunnel at Ames Research Center in Calif. (see Figure 6). Providers have used the wind tunnel for obtaining force/moment measurement of various first stage configurations to support vehicle re-entry. Additional Unitary Plan Wind Tunnel testing is planned for Fall 2025 with the Ames team participating in model

Figure 6. Through Government Task Agreements (GTAs), commercial providers can access the Unitary Wind Tunnel to evaluate aerodynamics of launch vehicles.

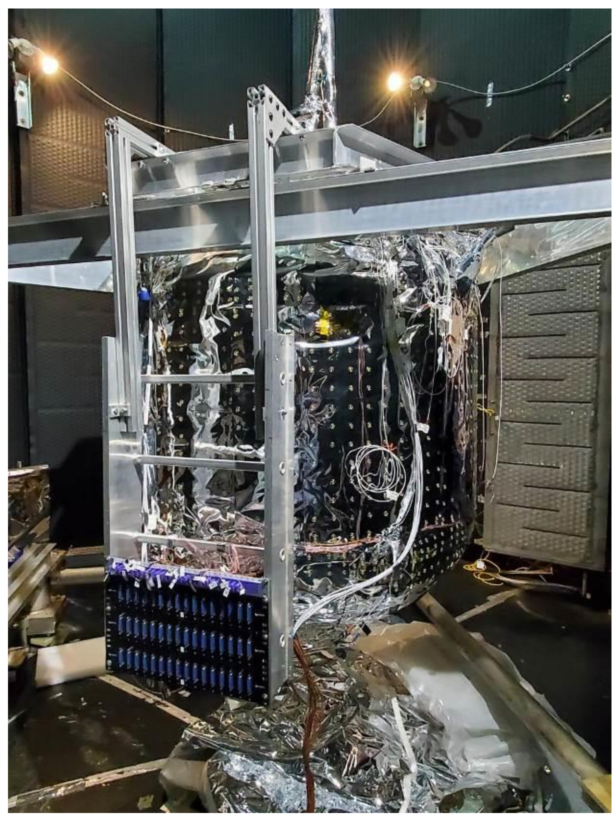

Figure 7. NASA Marshall’s Test Stand 300 is available for Collaborations and GTAs to test and evaluate cryogenic storage technologies. A 20-foot vacuum chamber also provides testing capabilities for engine and thruster subsystems and configurations.

design and fabrication meetings with commercial providers.

Marshall's Test Stand 300, a 91.4 m (300-foot) multi-position test stand, is used to test a range of launch vehicle engine components, systems, and subsystems (see Figure 7). It has the capability to simulate launch thermal and pressure profiles. Commercial providers can access Test Stand 300 through a GTA for activities including testing hot gas reaction control system (RCS) thrusters as well as for

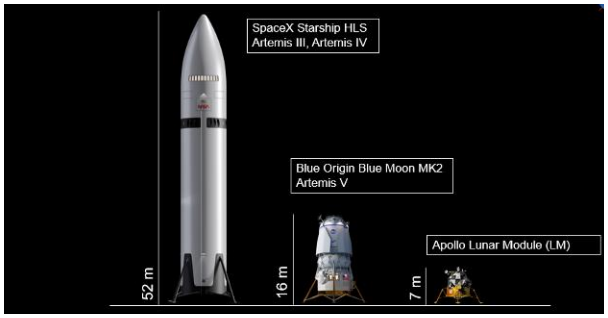

Figure 8. Height comparisons between HLS Artemis human-class lunar landers and Apollo Lunar Module (LM).

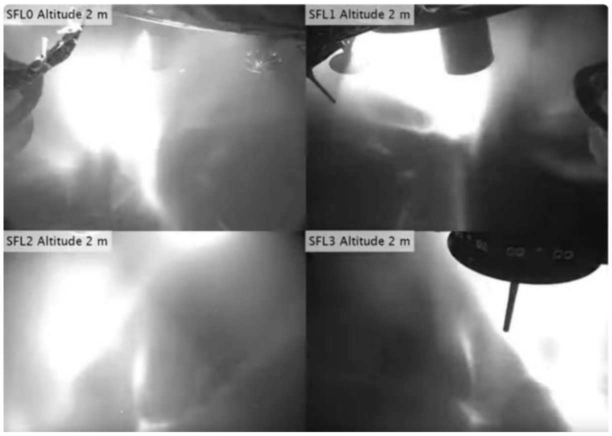

Figure 9. NASA's The Stereo Cameras for Lunar-Plume Surface Studies (SCALPSS) imaged PSI during descent and successful soft landing of Firefly Aerospace's Blue Ghost lunar lander on the Moon's Mare Crisium region, as part of NASA's Commercial Lunar Payload Services (CLPS) initiative. SCALPSS is scheduled to fly again on Blue Origin's MK1 private lunar landing mission.

development of long-duration, cryogenic propellant feed valves. In fact, NASA's Cryogenic Fluid Management Portfolio Project is a cross-agency team based at NASA Marshall and Glenn Research Center that is comprised of more than 20 individual technology development activities working to advance the state of the art in CFM.

Figure 10. Engineers and technicians at NASA's Langley Research Center are setting up for the most instrumented and complex ground-based PSI test in a vacuum environment ever attempted. NASA's HLS program is sponsoring the test to reduce the risk of PSI during Artemis lunar landings.

NASA-initiated testing and reports. In addition to the partnering efforts initiated by industry, NASA's HLS program also invests in its own testing, research, and reports to share with both providers in areas where it identifies risk reduction is needed. One area of particular interest to industry and to NASA is plume-surface interaction, or the creation of craters and surface instability when landing on the Moon. NASA has limited data from Apollo missions, but the scale and mass of the commercial landers in development for Artemis dwarf the Apollo lunar module.

In addition, ejecta from the engine exhaust has the potential to affect engines, systems, and other surface assets. NASA has several initiatives in place to characterize plume-surface interaction. NASA provides data from the various sources to both commercial providers to inform designs.

NASA's Stereo Cameras for Lunar Plume-Surface

Figure 11. In 2025, NASA Marshall tested a hybrid motor for an upcoming PSI test in NASA Langley's 18.2 m (60 foot) spherical vacuum chamber.

Studies (SCALPSS) camera system flew as a payload on Firefly Aerospace's Blue Ghost lunar lander as part of its Commercial Lunar Payload Services (CLPS) contract. SCALPSS used multiple cameras to capture imagery during descent and landing of the Blue Ghost lander to study the interaction between the lander's rocket plume and the lunar regolith (see Figure 9). SCALPSS is also scheduled to fly as a payload on Blue Origin's Blue Moon MK1 lander. The Blue Moon MK1 is a smaller, cargo precursor version of the Blue Moon MK2 lander for HLS; it's a private industry risk-reduction initiative.

In additional to SCALPSS imagery, NASA is also preparing for the largest, most complex, and highly instrumented PSI test ever conducted (see Figure 10). The test is currently being set up at NASA's Langley Research Center in its 18.2 m (60 foot) spherical vacuum facility. To prepare for the PSI test, NASA Marshall recently tested a hybrid motor developed by Utah State University to ensure the motor will reliably ignite and is ready to fire into simulated lunar regolith in the vacuum chamber (see Figure 11). The upcoming test campaign will be scalable to flight-like conditions and feature a lunar-like exhaust plume firing into Black Point-1 (BP-1) lunar regolith simulant. The data from this test series, along with the SCALPSS data, will help anchor models to predict the effects of PSI for landing on the Moon and Mars.

In addition to the Collaborations, GTAs, and NASA-sponsored risk-reduction testing, NASA has also provided studies, historical reports, and best-practices documentation to the commercial providers on topics of

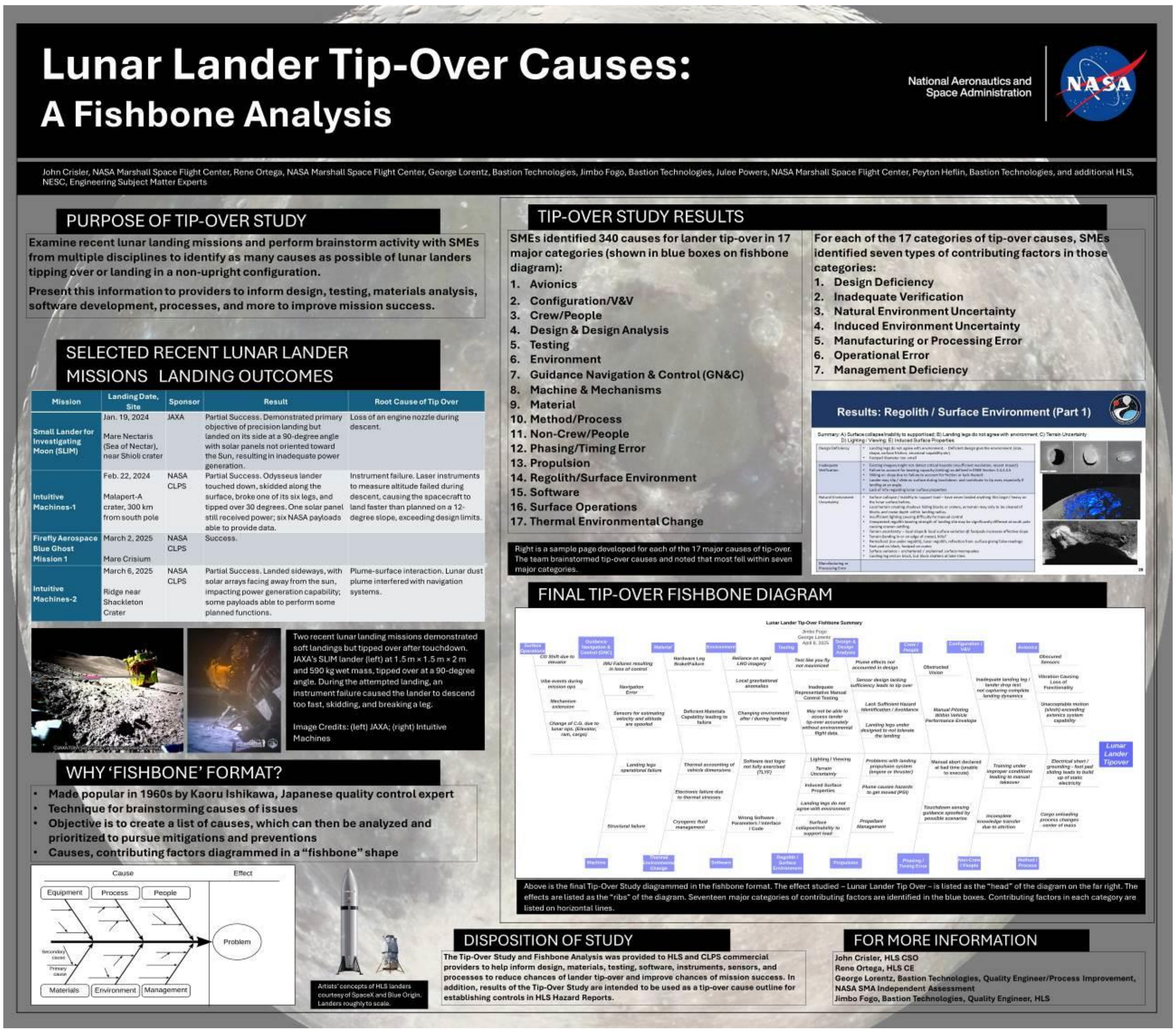

Figure 12. An integrated activity involving the HLS program, NASA Marshall's S&MA organization, and Bastion Technologies involved identifying and categorizing causes of lunar landers failing to land upright -- a failure mode seen in several landers in the last few years.

interest. NASA Marshall's CFM Portfolio Project Office generated a best-practices report outlining broad guidelines for in-space cryogenic propellant transfer. The report is intended to help commercial companies in the early phases of concept of operations (conops) development and includes general procedures for tank-to-tank transfer of cryogenic propellants for settled and unsettled conditions, as well as guidelines for cryocoupler construction, and safety considerations.

In addition to the CFM best-practices report, NASA Marshall's S&MA organization with safety contractor Bastion Technologies provided a study of lunar lander tip-over causes to the providers – particularly relevant after several smaller commercial and international-sponsored landers have failed to successfully land on the Moon. The lunar lander tip-over study identified 17 categories of anomalies that can cause a lander to fail to stay upright long enough to transmit data:

1. Avionics
2. Configuration/Verification & Validation
3. Crew/People
4. Design & Design Analysis
5. Testing
6. Environment
7. Guidance Navigation & Control (GN&C)
8. Machine & Mechanisms
9. Material
10. Method/Process
11. Non-Crew/People
12. Phasing/Timing Error
13. Propulsion
14. Regolith/Surface Environment
15. Software
16. Surface Operations
17. Thermal Environmental Change

The NASA S&MA team identified 340 causes of lunar lander tip-over that fit in the above 17 categories. The final tip-over analysis, formatted as an Ishikawa diagram (see Figure 12), was provided to the HLS and CLPS commercial providers to help inform design, materials, testing, software, instruments, sensors, and processes to reduce chances of lander tip-over and improve chances of mission success.

Although the HLS program does not dictate providers' design decisions, the program does exercise insight into key areas of development and use collaborations, GTAs, testing, and other channels to help ensure final designs will meet mission requirements. It is this key partnership between NASA and private industry that will usher in the Artemis era of deep space exploration.

4. Progress Toward Artemis III

Artemis III Conops. A few months prior to the Artemis III crew launching aboard SLS and Orion, the Starship HLS will begin its launch campaign, culminating in a Lunar Orbit Checkout Review (LOCR). Crew will not launch until LOCR is complete. To get to LOCR – where NASA assumes mission responsibility– SpaceX will utilize on-orbit cryogenic refueling. A "depot" Starship variant will launch first. The depot is optimized for propellant storage and mitigation of cryogenic propellant boiloff. SpaceX is testing various thermal protection system options, including multiple metallic tile options, and alternative materials during its ongoing test flight series. [1] After the Depot is on orbit, a series of Tankers will launch, transfer cryogenic methane (CH4) and liquid oxygen (LOX) to fill the Depot. The Starship HLS launches after the Tankers, docks with the Depot, and receives propellant. The Starship HLS will then head to NRHO for LOCR and await Orion and the crew.

After Orion-HLS docking, two crew will transfer from Orion into the Starship HLS and will descend to the surface, touching down near the Moon's South Pole region. Scheduled surface stay time for the crew is about six and one-half days. NASA is also working with commercial partner Axiom Space to develop new EVA suits, called Axiom Extravehicular Mobility Units (AxEMUs), for lunar surface expeditions. At the conclusion of surface operations, the two crew members will ascend from the lunar surface in the Starship HLS, dock with Orion, and re-unite with the other two crew members. Orion will safely bring the Artemis III crew back to Earth.

Major milestones prior to Artemis III. Prior to performing crewed lunar landings, both providers are required to demonstrate uncrewed lunar landings with their systems. For the uncrewed lunar landing demonstration prior to Artemis III, SpaceX is required to land a Starship HLS within 100 m (328 feet) of a target landing site near the lunar South Pole. The HLS will transmit data from the lunar surface, then lift off and achieve main engine combustion.

Prior to its uncrewed demonstration landing, SpaceX will demonstrate cryogenic propellant transfer operations in Earth orbit. Several CFM-related

Figure 13. Artist's illustration of the on-orbit cryogenic propellant transfer between SpaceX Depot (white) and Tanker (gray). (Image credit: SpaceX)

Collaborations are helping advance technology readiness in this area, as mentioned earlier.

Prior to the Artemis III lunar landing, the HLS program and SpaceX have mapped out numerous milestones, testing, and design reviews to ensure requirements are met as well as to reduce risks. SpaceX is working toward Critical Design Review (CDR) in 2026, which will signify the program is ready to proceed with system assembly, integration, and testing. Other NASA-required milestones include the Uncrewed Demonstration Landing, Design Certification Review (DCR), LOCR, and a post-mission assessment review.

Figure 14. SpaceX's rapid-cadence test flight campaign for its Super Heavy launch vehicle and Starship upper stage offered opportunities for iterative design and engineering refinements in 2025. (Image credit: SpaceX)

SpaceX continues with test flights from the company’s Starbase, Texas launch facility (see Figure 14). The company is working toward flying version 3 of its Starship vehicle, which is anticipated to be the version used for the Starship HLS and the Artemis III lunar landing. Each flight test incorporates lessons learned from the previous flight, and often stresses the vehicles involved in new ways, to enhance learning.

Progress on the crew compartment of the Starship HLS has included construction of a crew cabin mock-up for human factors testing and evaluation of aspects of the ECLSS and thermal control system. In addition, astronaut crews participated in and provided feedback on development of training activities to assess landing trajectories and aspects of vehicle piloting during landing. Material flammability testing has been ongoing with results feeding a trade study evaluating various atmospheres for the cabin. SpaceX has also performed development testing and analyses on crew displays, the elevator that will take crew from the airlock deck to the lunar surface and back again, solar array deployment, thermal and micro-meteoroid orbital debris (MMOD) protection tiles, landing legs, docking mechanisms, landing software and sensors, medical systems, and more. [2]

A vacuum Raptor cold-start demonstration test was successfully completed at SpaceX’s McGregor, Tex. development facility in 2023. This test demonstrated start operations across a range of parameters, including extreme cold. In addition to the successful cold start vacuum Raptor testing, SpaceX continues to upgrade the Raptors, incorporating additively manufactured parts and assemblies. In addition to engine and flight testing, SpaceX demonstrated internal tank-to-tank cryogenic propellant transfer, as required by its Tipping Point award. [3] The on-orbit demonstration consisted of transferring LOX between the header and main tanks within Starship.

In addition to flight testing, SpaceX is constructing a second orbital launch pad at its Starbase, Texas launch facilities. Work is also in progress at Kennedy Space Center for launching Starship from Launch Complex 39A. In 2026, SpaceX is expected to demonstrate the large-scale cryogenic propellant transfer test mentioned earlier, as well as testing the Starship HLS on-orbit for a long duration (see Figure 13). It is possible that these two tests may be performed back-to-back in Earth orbit. The objectives for the long-duration test would be performed first, with the large-scape propellant transfer test performed at the end of the orbital duration. The long-duration cryogenic propellant transfer test is expected to generate valuable data to help reduce the risk associated with orbital cryogenic propellant transfer.

5. Progress Toward Artemis IV

Recognizing the need to balance mission schedules that include elements of the deep space architecture from numerous commercial providers with ever-increasing mission capabilities, the agency decided that human landing missions after Artemis III will require a more capable lander. In 2022, the agency awarded SpaceX a contract modification to provide a Starship HLS that meets a more robust set of requirements for a second human lunar landing, scheduled for Artemis IV. The Artemis IV mission and subsequent missions will require HLS to support landing a crew of up to four and have the capability to land and operate for extended durations at the lunar south pole as well the ability to land at non-polar sites. The HLS will also require additional performance capabilities to enable increased up-mass and down-mass, and extended EVA duration and frequency. All missions after Artemis III will require the HLS to dock with Gateway.

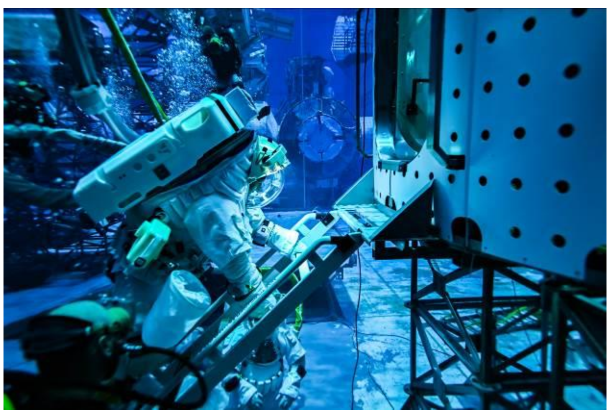

Figure 15. Blue Origin completed several test runs in NASA Johnson Space Center's Neutral Buoyancy Lab (NBL) where divers practiced ingress and egress of a Blue Moon MK2 mockup in the pool. (Image credit: Blue Origin)

6. Progress Toward Artemis V

In spring 2023, NASA awarded Blue Origin a contract to develop an HLS built to the same robust requirement set as Artemis IV. Blue Origin is developing the Blue Moon MK2 lander for the Artemis V lunar landing (see Figure 4). The HLS program and Blue Origin have completed several activities focused on design and construction standards, requirements, interface definitions, integration, and design reviews, including a Certification Baseline Review (CBR). Following successful completion of a standards adjudication process, where the provider was required to meet a standard or show that it was meeting the intent of the standard, and CBR, the HLS program and Blue Origin held a Preliminary Design Review (PDR) in February 2024 that covered design and analysis of the integrated lander architecture. Blue Origin is now working toward CDR in 2026.

Blue Origin is developing its BE-4 engines to propel the first stage of its New Glenn launch vehicle. BE-4 engines are tested and qualified at the company’s Van Horn, Tex. facility and manufactured at the company’s Huntsville, Ala. rocket engine factory, as are the company’s BE-3 engines for the New Glenn second stage. Blue Origin is developing its BE-7 engine to propel the Blue Moon lander; these engines are also built in Huntsville. A BE-7 development engine recently initiated vacuum chamber testing at the Air Force Research Lab (AFRL) at NASA’s Armstrong Flight Research Center. In addition, Blue Origin delivered of a medium-fidelity mockup of the Blue Moon MK2 Crew Compartment to Johnson Space Center in Houston December 2025.

Blue Origin’s New Glenn launch vehicle successfully completed ascent and payload delivery to

Figure 16. Artist's illustration of the SpaceX Starship large cargo lunar lander. (Image credit: SpaceX).

Figure 17. Artist's illustration of the Blue Origin Blue Moon MK2 large cargo lunar lander. (Image credit: Blue Origin)

orbit in January 2025. New Glenn will be the launch vehicle for the Blue Moon MK2 lunar lander. In addition, in 2025, divers at NASA’s Johnson Space

Center equipped with space suit mockups successfully completed several tests in the Neutral Buoyancy Lab (NBL) with a mockup of the lunar lander. Blue Origin and NASA were able to evaluate ingress and egress during the NBL tests (see Figure 15).

7. Large Cargo Lunar Landers

In 2023, the HLS program exercised contract modifications giving providers SpaceX and Blue Origin authority to proceed with work on large-scale cargo landers that will deliver 12-15 t of payload to the lunar surface. See Figures 16 and 17 for initial concepts of these landers. These large cargo landers leverage designs of the companies' HLS landers for crew, with significant systems commonality, but instead of accommodations for crew, they will have interfaces for large cargo and specialized deployment mechanisms for offloading cargo to the lunar surface. The contracts include delivery from Earth and are not dependent on the timing of any Artemis missions. SpaceX and Blue Origin have each completed a CBR for their cargo landers and are working toward Preliminary Design Reviews. The large cargo landers are required to be able to operate autonomously and a payload delivery using a cargo lander could occur between crewed Artemis missions. In November 2024, NASA announced its intent to for SpaceX's Starship-based cargo lander to deliver a pressurized rover, currently in development by Japan Aerospace Exploration Agency (JAXA), to the lunar surface no earlier than fiscal year 2032. The agency expects Blue Origin to deliver a lunar surface habitat using its Blue Moon MK2-based cargo lander no earlier than fiscal year 2033. As NASA's program charged with responsibility for procuring landing services for the Moon and Mars, the HLS program can offer a certified landing capability with high reliability for large cargo delivery and offloading.

8. Conclusion

Following the success of the Artemis I test flight, NASA is nearing its first crewed flight to cislunar space, Artemis II. Expected to launch in spring 2026, Artemis II will send four astronauts on a powered lunar flyby and test the Orion spacecraft's handling qualities and ECLSS. Building on Artemis II, NASA will land two crew on the Moon for Artemis III, using industry-designed and developed landers that NASA's HLS program has exercised risk-based insight into.

Following Artemis III, NASA plans to regularly transport crew and large payloads to Moon to set up a sustainable infrastructure for exploration, discovery, and science. With NASA leading the Artemis missions and aligning with other countries of the world to enable peaceful science and discovery of the Moon through the Artemis Accords, a golden era of human exploration and discovery in space dawns.

9. References

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