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NASA's Readiness for the Artemis II Crewed Mission to Lunar Orbit

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Results in Brief

NASA's Readiness for the Artemis II Crewed Mission to Lunar Orbit

May 1, 2024 IG-24-011 (A-23-07-00-HED)

Why We Performed This Audit

With the Artemis campaign, NASA intends to return humans to the Moon and build a sustainable lunar presence as a foundation for human exploration of Mars. The uncrewed Artemis I test flight was completed in December 2022 and was a significant achievement for the Agency, providing important data and lessons learned from the testing of hardware, software, processes, and teams that will prepare NASA for future Artemis missions. The Artemis II crewed test flight aims to return humans to lunar orbit for the first time in more than 50 years and send its four crew members farther into space than any human has ever gone. Like Artemis I, the Artemis II mission will utilize the Space Launch System (SLS), a two-stage, heavy-lift rocket that will launch the Orion Multi-Purpose Crew Vehicle (Orion) capsule into space from the Mobile Launcher 1 (ML-1) at Kennedy Space Center. By September 2025, the planned launch date for Artemis II, NASA will have spent more than $55 billion on the SLS, Orion, and Exploration Ground Systems (EGS) programs.

Given the high stakes of the first crewed flight, the Agency is working to identify and mitigate any risks and challenges to ensure the safe return of the Artemis II crew and safeguard NASA's significant investment in Artemis vehicles and systems. In particular, the Agency must address the risks identified in the Artemis I Post-Flight Assessment Review, execute planned modifications and upgrades required to support the Artemis II astronauts, and complete stacking and testing of the integrated SLS and Orion. In light of ongoing work to address issues with the Orion spacecraft, in January 2024, the Agency announced that it would push the Artemis II launch date from November 2024 to September 2025.

In this audit, we examined NASA's readiness for the Artemis II crewed mission to lunar orbit. To complete this work, we conducted a site visit at Kennedy Space Center and interviewed officials with the Exploration Systems Development Mission Directorate; SLS, Orion, EGS, and Space Communications and Navigation programs; and other technical experts and stakeholders. To determine the extent to which Artemis I met its objectives, we reviewed key documents to evaluate mission performance as well as NASA's mission coverage and preliminary flight reviews.

What We Found

As a test flight, Artemis I was used to examine how the integrated SLS and Orion and associated systems performed in their intended environment, allowing the Agency to confidently mitigate risks, certify system designs, and validate mission capabilities for future missions in the Artemis campaign. To this end, the Artemis I test flight revealed critical issues that need to be addressed before placing crew on the Artemis II mission. In particular, the test flight revealed anomalies with the Orion heat shield, separation bolts, and power distribution that pose significant risks to the safety of the crew. Resolution of these anomalies is among the most significant factors impacting NASA's readiness for Artemis II. To its credit, the Agency is taking action to address these issues.

Specifically, NASA identified more than 100 locations where ablative thermal protective material from Orion's heat shield wore away differently than expected during reentry into Earth's atmosphere. Engineers are concurrently investigating ways to mitigate the char loss by modifying the heat shield's design or altering Orion's reentry trajectory. In addition, post-flight inspections of the Crew Module/Service Module separation bolts revealed unexpected melting and erosion that created a gap leading to increased heating inside the bolt. To mitigate the issue for Artemis II, the Orion Program made minor modifications to the separation bolt design and added additional thermal protective barrier material in the bolt gaps. NASA also recorded 24 instances of power distribution anomalies in Orion's Electrical Power

System. While NASA has determined that radiation was the root cause and is making software changes and developing operational workarounds for Artemis II, without a permanent hardware fix, there is increased risk that further power distribution anomalies could lead to a loss of redundancy, inadequate power, and potential loss of vehicle propulsion and pressurization. Moreover, like with any engineering system, without understanding the residual effects of introducing design and operational changes, it will be difficult for the Agency to ensure that the mitigations or hardware changes adopted will effectively reduce the risks to astronaut safety.

Beyond the Orion anomalies, the Artemis I launch-induced environment caused greater than expected damage to ML-1 elevators, electrical equipment, enclosure panel doors, and pneumatic tubing, requiring extensive repairs that will cost more than $26 million, roughly 5 times more than the $5 million the EGS Program had originally set aside for post-Artemis I launch repairs. Additionally, a loss of in-flight communications revealed hardware and process issues with the Deep Space Network that can largely be attributed to maintenance deferrals and deterioration of hardware, which have been long-standing issues for the network. NASA has begun taking corrective actions to mitigate the issues that impacted Artemis I communications. Finally, we identified missed opportunities for data collection as a result of imagery issues, failure to recover jettisoned hardware after landing, and inaccessible telemetry data that have impacted NASA's ability to fully evaluate and address certain launch, landing, and recovery risks.

In addition to addressing the technical issues and risks discovered during the Artemis I test flight, NASA has further work and testing that it must complete to safely return humans to lunar orbit. NASA's planned work for Artemis II includes upgrades and modifications to the SLS, Orion, and ground facilities. Although NASA is making progress, verification and validation testing for some of these upgrades and modifications is taking longer than expected. Furthermore, during recent qualification and acceptance testing of Orion's circuitry and Crew Module batteries, NASA discovered hardware defects that increase crew safety risks. Regarding the circuitry issues, NASA is working to make modifications to hardware in difficult-to-access locations inside the already assembled Orion spacecraft and perform additional tests. The investigation into the battery issues is in the early stages, and NASA has not yet identified a resolution.

While NASA's decision to push the Artemis II launch date will provide the Agency with more time to prepare for the first crewed mission, NASA will need to balance its time frame for corrective actions with the start of stacking the components of the SLS and Orion on the ML-1. Once stacking of the integrated systems begins, NASA must carefully monitor and track key Artemis II hardware, such as the SLS solid rocket boosters, that have a limited operating life before requiring servicing or replacement. Premature stacking could create risk of further cost increases and additional schedule delays.

What We Recommended

To ensure the safety of the crewed Artemis II mission, we recommended the Associate Administrator for Exploration Systems Development Mission Directorate: (1) ensure the root cause of Orion heat shield char liberation is well understood prior to launch of the Artemis II mission; (2) conduct analysis of Orion separation bolts using updated models that account for char loss, design modifications, and operational changes to Orion prior to launch of the Artemis II mission; (3) require EGS conduct additional verification and validation for launch imagery equipment prior to launch attempts should launch conditions change; (4) reexamine procedures to better ensure recovery of Orion jettisoned hardware for the Artemis II mission; (5) develop a corrective action plan to mitigate or prevent the recurrence of uninterpretable Orion telemetry data for the Artemis II mission; and (6) establish a course of action and timeline for individual Artemis system design changes before beginning integrated system assembly stacking operations.

We provided a draft of this report to NASA management who concurred with our recommendations and described planned actions to address them. We consider the proposed actions responsive and will close the recommendations upon completion and verification. While the Agency noted that its planned actions have been completed for Recommendations 4, 5, and 6, we were not provided evidence of these actions prior to issuance of this report.

For more information on the NASA Office of Inspector General and to view this and other reports visit https://oig.nasa.gov/.

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Acronyms

DSN	Deep Space Network
ECLSS	Environmental Control and Life Support System
ECS	Environmental Control System
EGS	Exploration Ground Systems
ESDMD	Exploration Systems Development Mission Directorate
Hz	hertz
ICPS	Interim Cryogenic Propulsion Stage
LOLI	limited operating life item
ML-1	Mobile Launcher 1
NSN	Near Space Network
OIG	Office of Inspector General
PCA	Private Cloud Appliance
PCDU	Power Conditioning and Distribution Unit
PFAR	Post-Flight Assessment Review
SCaN	Space Communications and Navigation
SLS	Space Launch System
VAB	Vehicle Assembly Building

INTRODUCTION

With the Artemis campaign, NASA intends to return humans to the Moon and build a sustainable lunar presence as a foundation for human exploration of Mars. After more than a decade of preparation and several delays, the first mission—Artemis I—was completed in December 2022 and served as the first and only integrated uncrewed test flight of NASA's deep space exploration systems. Artemis I was a significant achievement for NASA, providing important data and lessons learned from the testing of hardware, software, processes, and teams that will help prepare the Agency for future Artemis missions.

Currently in preparation, Artemis II aims to return humans to lunar orbit for the first time in more than 50 years and send its four crew members farther into space than any human has ever gone. Like Artemis I, the Artemis II mission will utilize the Space Launch System (SLS), a two-stage, heavy-lift rocket that will launch the Orion Multi-Purpose Crew Vehicle (Orion) capsule into space from the Exploration Ground Systems' (EGS) launch facilities. However, before NASA can launch Artemis II, the Agency must address the risks identified in the Artemis I Post-Flight Assessment Review, execute planned modifications and upgrades required to support the Artemis II astronauts onboard, and complete stacking and testing of the integrated SLS and Orion.

By September 2025—NASA's planned Artemis II launch date—the Agency will have spent more than $55 billion on SLS, Orion, and the ground systems needed for the Artemis missions. Given the high stakes of the first crewed flight, the Agency is working to identify and mitigate any risks and challenges to ensure the safe return of the Artemis II crew while safeguarding NASA's significant investment in Artemis vehicles and systems. In this audit, we examined NASA's readiness for the Artemis II crewed mission to lunar orbit.

Background

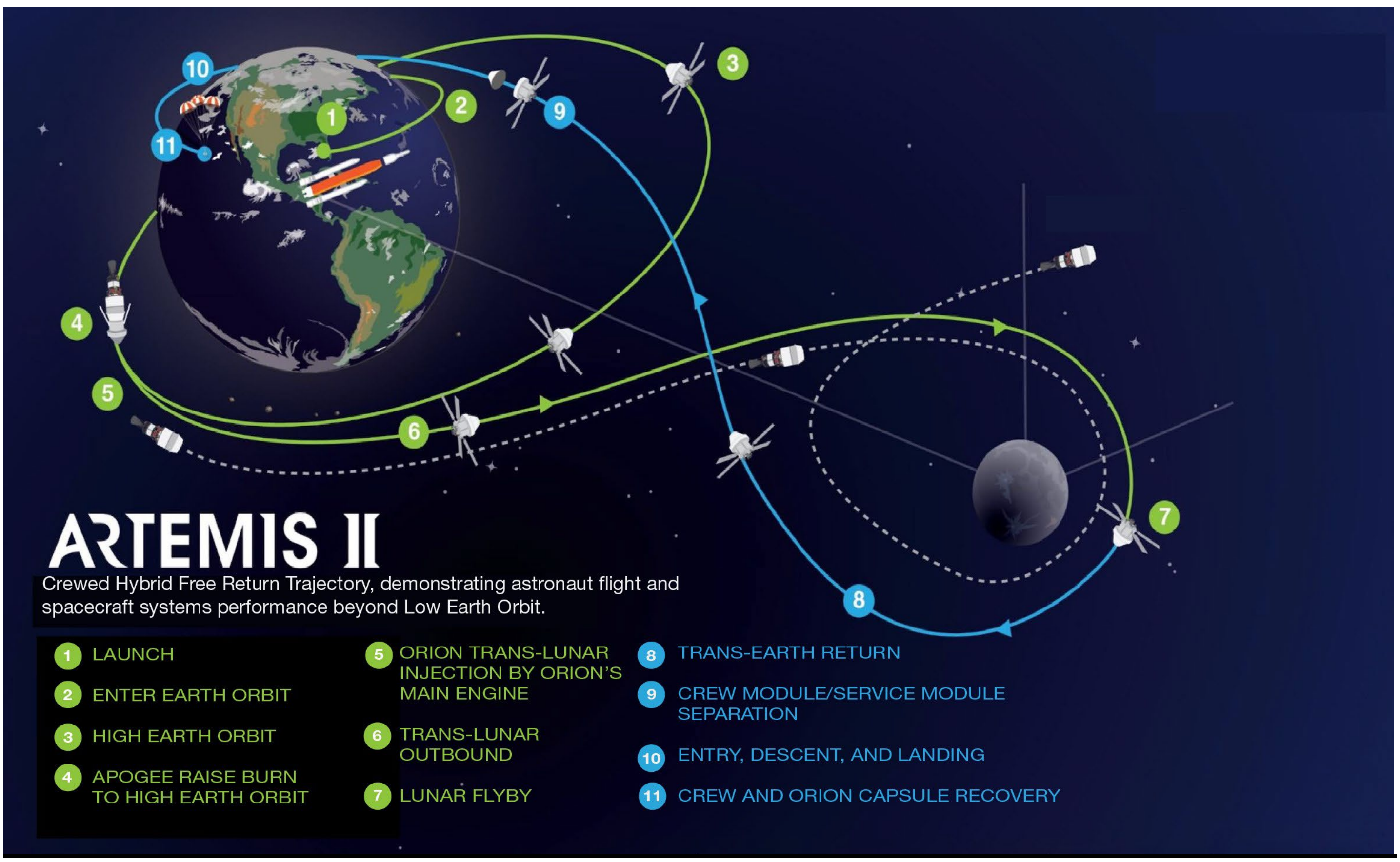
The Artemis campaign is a series of increasingly complex missions that will build upon each other to establish a long-term human presence on the Moon and ultimately Mars. Key to this goal is the success of the first two Artemis missions, which are the uncrewed and crewed test flights for NASA's interdependent deep space exploration systems.

Flight testing allows NASA to learn how systems and operations perform both on the ground and in the actual flight environment. As such, NASA utilizes flight tests to mitigate risks by collecting data to certify its designs and validate mission capabilities by seeing how systems perform in their intended environment. Although the Agency conducts extensive system testing pre-flight, there are many attributes of space flight that cannot be replicated on the ground or adequately emulated in modeling or pre-launch testing. Flight testing also allows NASA to identify and document lessons learned, the application of which is essential to the success of future missions.

The Artemis I mission provided significant flight and systems performance data in cislunar space that cannot be replicated on Earth.[1] As an uncrewed test flight, the primary goals of the Artemis I mission were to thoroughly test the integrated systems in the flight environment by launching Orion atop the SLS rocket, operating the spacecraft in a deep space environment, testing Orion's heat shield, and recovering the Crew Module after reentry, descent, and splashdown. Artemis I successfully completed its mission milestones, including all vehicle separations, an orbit around the Earth, a trans-lunar injection, a lunar orbit that came within 80 miles of the Moon's surface, a reentry into Earth's atmosphere, and a landing and recovery of the Orion capsule in the Pacific Ocean.

In preparation for the Artemis II crewed test flight, NASA is conducting ground tests to demonstrate to the extent possible the hardware, software, processes, and human interfaces necessary to safely fly and sustain astronauts in space. NASA is scheduled to launch Artemis II in September 2025 for a 10-day mission to orbit the Moon (see Figure 1).[2] After conducting a 23.5-hour checkout of the spacecraft's systems in high Earth orbit, Orion will embark on a trajectory to reach the far side of the Moon and harness the Earth-Moon gravity field to pull the vehicle back to Earth.[3]

Figure 1: Artemis II Planned Flight Path



Source: NASA.

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1 Cislunar is the space between the Earth and the Moon or the Moon's orbit.

2 In January 2024, NASA announced that the launch date for the Artemis II mission would be delayed from November 2024 to September 2025.

3 High Earth orbit sits about 36,000 kilometers above the Earth's surface.

Like Artemis I, Artemis II's goals include demonstrating the capabilities and performance of the integrated systems, especially the Orion spacecraft. With crew onboard, NASA plans to further evaluate critical survival and life support systems that were not included or fully tested during Artemis I. For example, Artemis II will test the crew interface displays and controls, the emergency and recovery communications equipment, a stowage system with crew support equipment, and the Environmental Control and Life Support System (ECLSS).[4] In addition, Artemis II will feature equipment designed to ensure the safety of the crew in the event of an emergency during ground, launch, and ascent operations. These include a launch pad crew escape system and an active Launch Abort System. See Table 1 for a summary comparison between the Artemis I and II missions.

Table 1: Comparison of Artemis I and Artemis II Missions and Objectives

Artemis I	Artemis II
Uncrewed Test Flight	Crewed Test Flight
Deep Space Exploration Systems used: SLS, Orion, and EGS	Deep Space Exploration Systems used: SLS, Orion, and EGS
25.5-day mission	Less than 10-day mission
Objectives: • Demonstrate the performance of Orion's heat shield at lunar reentry conditions • Operate systems in flight environment • Retrieve Orion spacecraft • Accomplish additional test flight objectives	Objectives: • Evaluate crewed system performance for SLS and Orion in the deep space environment • Demonstrate systems and operations essential to a crewed lunar campaign • Retrieve flight hardware and data • Demonstrate emergency and off-nominal system capabilities and validate associated operations to the extent practical • Accomplish additional test flight objectives

Source: NASA Office of Inspector General (OIG) presentation of NASA information.

Artemis II is NASA's only planned test mission with crew before attempting to land humans on the Moon during the Artemis III mission. With the addition of crew to a mission, NASA must incorporate human rating requirements into mission readiness. Human rating requirements are intended to ensure that space systems carrying crew receive additional rigor and scrutiny in their design, development, certification, and operation. The human rating certification process at NASA focuses on what reasonable steps programs have taken in designing their space systems and translating those design limits into operational plans and procedures to minimize the potential for loss of life or risk of injury. A human-rated system ensures the safety of crew, accommodates human needs, utilizes human capabilities, controls hazards, manages safety risks, and provides capability to safely recover the crew from hazardous situations. In addition to basic human needs such as environment, food, and water, the astronauts must have some control over the space system and its operation.[5] For example, NASA requirements dictate the crew have manual control of Orion's flight path and attitude, as well as the ability to manually override software control and automation.[6]

[4] ECLSS provides a habitable atmosphere for the crew. NASA did not fully test Orion's ECLSS on Artemis I because portions of the required hardware were not installed and crew were not present to allow appropriate exercising of life support systems.

[5] Environment includes cabin temperature, pressure, humidity, oxygen, and carbon dioxide levels.

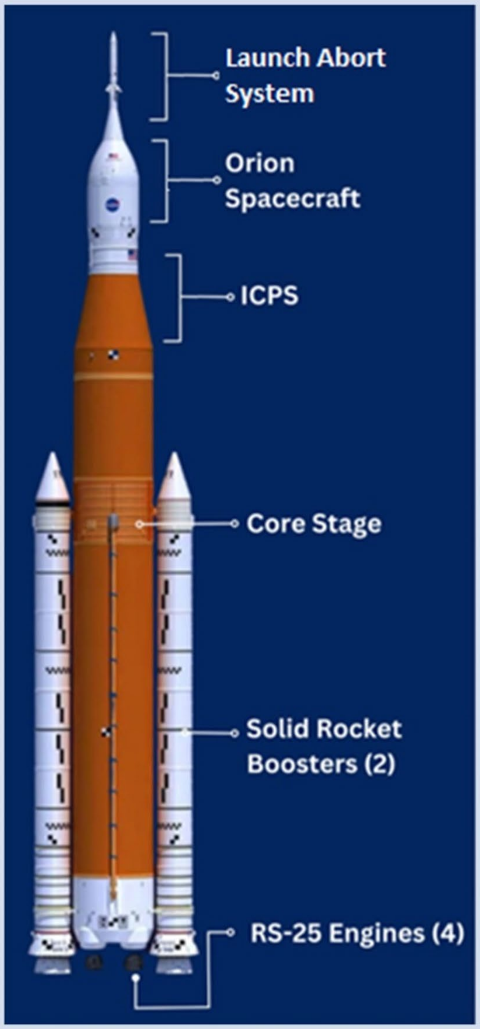
[6] Attitude is the direction the vehicle is pointed.

Artemis II Systems

Space Launch System

As directed by the NASA Authorization Act of 2010, NASA developed the SLS, which is the first exploration-class launch vehicle since the Apollo Program's Saturn V rocket.[7] Its current design—the SLS Block 1 configuration—will be used for the first three Artemis missions and will be able to deliver 27 metric tons to lunar orbit. This configuration includes the core stage that consists of propellant tanks that hold over 730,000 gallons of liquid hydrogen and liquid oxygen that fuel the rocket's four RS-25 engines, two solid rocket boosters that provide over 75 percent of the vehicle's thrust during the initial minutes of flight, and an Interim Cryogenic Propulsion Stage (ICPS) responsible for propelling the Orion spacecraft to the Moon.[8]

SLS Block 1 Configuration



The first three Artemis missions will use SLS's Block 1 configuration consisting of four RS-25 engines, two solid rocket boosters, a core stage, and the ICPS. The Orion spacecraft sits atop the SLS.

Source: NASA OIG.

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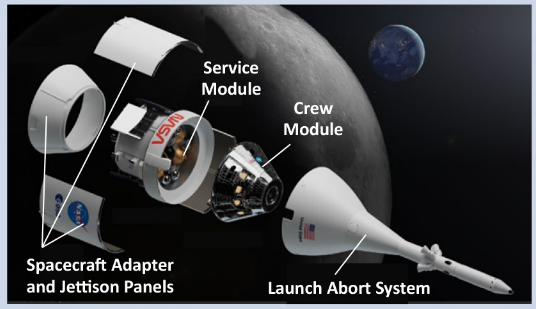
[7] NASA Authorization Act of 2010, Pub. L. No. 111-267 (2010).

[8] Beginning with the Artemis IV mission, NASA will evolve the SLS to the bigger and more powerful configuration known as SLS Block 1B, which will replace the ICPS with the Exploration Upper Stage. For later missions starting with Artemis IX, NASA will upgrade the SLS for a third time to the SLS Block 2 configuration, which will improve the solid rocket boosters.

Orion Multi-Purpose Crew Vehicle

Orion will serve as the spacecraft to carry and sustain astronauts during their journey to and from lunar orbit. Orion consists of a spacecraft adapter, Service Module, Crew Module, and Launch Abort System. While the adapter joins the Orion to the SLS's upper stage, the Service Module provides the spacecraft with support systems, including electricity, propulsion, thermal control, air, and water. The Crew Module is a pressurized capsule providing living space for the crew. The module can accommodate 4 astronauts for up to 21 days and provides life support, avionics, power systems, a heat shield for thermal protection, and a parachute system in support of a safe reentry to Earth. Lastly, Orion includes the Launch Abort System, which is designed to protect astronauts if a problem arises during launch by pulling the spacecraft away from the rocket in the case of an emergency.

Breakout of Orion Components



Source: NASA.

Exploration Ground Systems

Based at NASA's Kennedy Space Center in Florida, the EGS Program develops and operates the facilities and ground support necessary to assemble, transport, and launch rockets and spacecraft. These facilities include the Vehicle Assembly Building (VAB), where the SLS and Orion are stacked and fully integrated; Launch Pad 39B, from which the integrated SLS and Orion launches; and Mobile Launcher 1 (ML-1), which is used to assemble the SLS and Orion, transport the integrated vehicle to the launch pad, and provide power, communications, coolant, fuel, stabilization, and crew access prior to launch.[9] The Program is also responsible for Artemis launch operations, including preparing the launch pad and coordinating launch activities from the Launch Control Center. After the splashdown of Orion, the EGS Program leads recovery operations of the vehicle and crew.

Artemis I SLS/Orion Rollback to the VAB on ML-1

The ML-1, carrying the integrated SLS and Orion, returns to the VAB in September 2022 for shelter during Hurricane Ian.

Source: NASA.

[9] To support larger variants of the SLS beginning with the Artemis IV mission, NASA is building a second mobile launcher—Mobile Launcher 2.

Space Communications and Navigation

The Artemis missions also rely on communications and navigation capabilities provided by NASA's Space Communications and Navigation (SCaN) Program. As part of NASA's Space Operations Mission Directorate, SCaN manages both the Agency's Near Space Network (NSN) and Deep Space Network (DSN), which provide flight controllers spacecraft tracking and telemetry data and allows them to send and receive spacecraft commands using radio waves.[10]

- **Near Space Network.** NSN relies on a combination of commercial and government-owned, contractor-operated assets, including 22 ground antennas located around the world and a constellation of tracking and data relay satellites, to provide communication and navigation services to launch vehicles, robotics, and crewed space flight missions. For Artemis missions, the NSN Direct-to-Earth service is used to track the mission during launch and early phases of ascent, while the Tracking and Data Relay Satellite system provides tracking data during the mission's orbital ascent and return to Earth.[11]
- **Deep Space Network.** DSN operates antennas and transmitters at communication complexes in three facilities spaced equidistant from each other around the world: Goldstone, California; Madrid, Spain; and Canberra, Australia.[12] These locations are strategically placed to allow constant communication with spacecraft as the Earth rotates, a model called "Follow the Sun." Under this model, each site operates the entire network during their day shift, handing off control to the next site as their day ends. The Artemis missions rely on DSN to provide communications with the crew onboard, receive imagery from the Orion capsule, and send commands to the spacecraft while en route to and in orbit around the Moon and when returning to Earth.

Currently, more than 100 missions rely on SCaN's NSN and DSN services, including uncrewed scientific space probe missions from NASA's Science Mission Directorate, as well as other U.S. government agencies and international partners. For the Artemis missions, DSN will need to support a constant flow of data with the Orion capsule, which will require complex coordination throughout the Agency. In July 2023, we reported that DSN is oversubscribed and overburdened with demands due to the increasing number of missions it supports and recommended NASA explore more efficient options for DSN scheduling, such as maintaining a list of network users by priority.[13]

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[10] Tracking is the function that allows flight controllers to determine the position and velocity of a spacecraft with great precision. Telemetry is the collection, processing, and transmission back to Earth of a spacecraft's performance data. Command is the function that allows remote control of a spacecraft.

[11] NSN provides two categories of communication services: (1) Direct-to-Earth enables direct communication between a spacecraft and antennas on Earth and (2) Tracking Data and Relay Satellites provide communication between a spacecraft and one of many satellites in Earth's orbit that connects to a ground antenna.

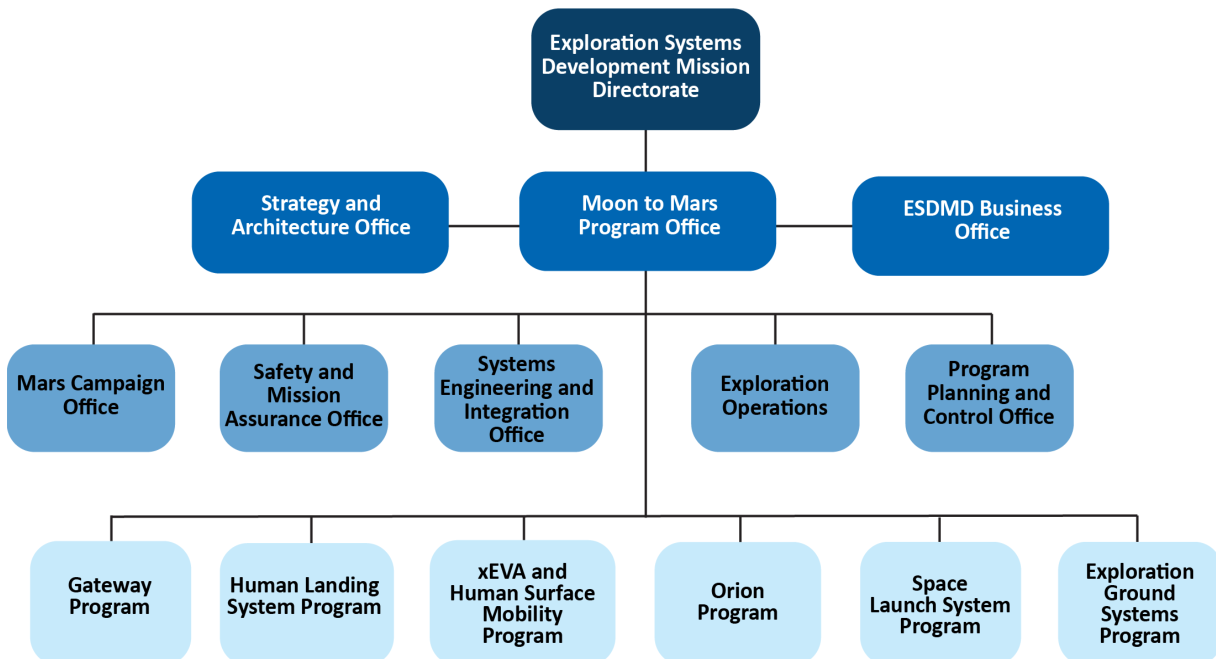
[12] NASA has agreements with the Spanish and Australian governments to manage day-to-day operations at the foreign sites together with the Jet Propulsion Laboratory, a federally funded research and development center in Pasadena, California, for the Goldstone site.

[13] NASA Office of Inspector General (OIG), *Audit of NASA's Deep Space Network* (IG-23-016, July 12, 2023).

Artemis Campaign Management

NASA's Exploration Systems Development Mission Directorate (ESDMD) is responsible for managing development of systems and programs critical for the Artemis campaign and for planning the Agency's Moon to Mars exploration approach. As directed by the 2022 NASA Authorization Act, NASA established the Moon to Mars Program Office within ESDMD to focus on hardware development, mission integration, and risk management functions critical to the Agency's deep space exploration goals.[14] The Moon to Mars Program Office oversees development of the SLS rocket, Orion spacecraft, and supporting ground systems, in addition to other systems—such as spacesuits and the human landing system—needed for future Artemis missions (see Figure 2).

Figure 2: NASA's Exploration Systems Development Mission Directorate Organization Chart



Source: NASA OIG presentation of Agency information.

The Moon to Mars Program Office, on behalf of ESDMD, is responsible for overseeing the Post-Flight Assessment Review (PFAR)—a standardized review process conducted after each mission. As part of this process for the Artemis I mission, each of the mission elements, including the SLS, Orion, and EGS programs, conducted their own PFAR that then contributed to the overarching Moon to Mars PFAR. The PFAR is designed to evaluate how well Artemis I met its mission objectives, assess system performance, and identify any flight and ground system anomalies. The primary focus of this exercise is to assess NASA's readiness to proceed to the next mission—Artemis II. The information gathered informs the actions necessary to resolve or mitigate issues for future flights. Furthermore, engineers compare the actual vehicle performance to pre-flight modeling predictions to determine any necessary adjustments to subsequent missions. The Agency conducted the Artemis I PFAR in July 2023. As of February 2024, actions items identified during the PFAR process were still open and in work.

[14] NASA Authorization Act of 2022, Pub. L. No. 117-167 (2022).

Artemis I Test Flight Revealed Critical Issues That NASA Is Working to Address Before the Artemis II Mission

After more than a decade of development, NASA successfully completed the Artemis I mission, meeting all four of its primary objectives. Although the Artemis I test flight is considered by the Agency to be a significant achievement and sets the stage for the next missions in the Artemis campaign, the flight revealed several unexpected issues that NASA is working to address prior to the Artemis II launch. Specifically, anomalies with the Orion heat shield, separation bolts, and power disruptions pose potential risks to crew safety. Resolution of these issues is among the most significant factors impacting NASA's readiness for Artemis II and the safety of the crew. Moreover, greater than expected launch damage required significant repair to the ML-1 and an in-flight loss of communication event revealed hardware and process issues. In addition, we identified missed opportunities to optimize Artemis I data collection that could have an impact on the Artemis II mission. Collectively, these issues and the steps that NASA is taking to address them will impact the Agency's readiness for Artemis II and its ability to safely return humans to and from lunar orbit.

Orion Anomalies Pose Significant Safety Risks to the Crew

Heat Shield Char Loss

NASA identified more than 100 locations where ablative thermal protective material from Orion's heat shield chipped away unexpectedly during reentry into Earth's atmosphere. During descent, the spacecraft reached speeds of nearly 25,000 miles per hour and endured temperatures about half as hot as the surface of the Sun—nearly 5,000 degrees Fahrenheit. Orion's heat shield is designed to protect the Crew Module, its systems, and the crew from this intense heat during reentry. While the heat shield successfully protected the Crew Module and its systems during the Artemis I mission, upon inspection after Orion's recovery, engineers noted unexpected variations in the appearance of the heat shield Avcoat—the ablative material that helps protect the capsule from

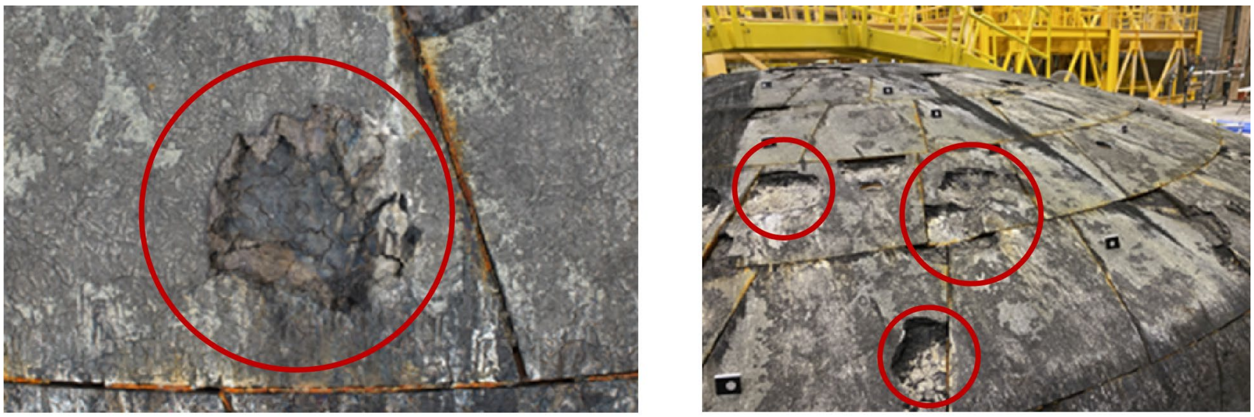
Orion Char Loss Debris during Artemis I Reentry

Onboard video from Orion during the Artemis I descent depicting char loss upon reentry to Earth's atmosphere.

Source: NASA.

the heat of reentry.[15] Specifically, portions of the char layer wore away differently than NASA engineers predicted, cracking and breaking off the spacecraft in fragments that created a trail of debris rather than melting away as designed (see Figure 3). The unexpected behavior of the Avcoat creates a risk that the heat shield may not sufficiently protect the capsule's systems and crew from the extreme heat of reentry on future missions. Moreover, while there was no evidence of impact with the Crew Module, the quantity and size of the debris could have caused enough structural damage to cause one of Orion's parachutes to fail. Should the same issue occur on future Artemis missions, it could lead to the loss of the vehicle or crew.

Figure 3: Orion Heat Shield Char Loss After Artemis I Mission



Images show heat shield char loss post-Artemis I mission, including cavities resulting from the loss of large chunks of the heat shield char during reentry.

Source: NASA.

In our judgment, the unexpected behavior of the heat shield poses a significant risk to the safety of future crewed missions. Recognizing this threat, NASA formed a Tiger Team to investigate the char loss phenomenon.[16] The team's ability to reproduce and model the char loss conditions will influence NASA's corrective actions going forward. Engineers are conducting ground tests to understand the Avcoat material's thermal response. Although they were able to recreate the char loss, they could not reproduce the exact material response or flight environment experienced during Artemis I. Ultimately, ground testing cannot replicate the exact temperature and speed conditions the heat shield faces during reentry. In comparison, Orion's velocity is about 40 percent faster than what astronauts face in a SpaceX Crew Dragon on its return from the International Space Station due to the greater distance Orion must travel to return to Earth. The ongoing investigation is scheduled to conclude in the first half of 2024 following further ground testing.

Senior NASA leaders expressed commitment to identifying the root cause of the char loss condition and making a data-informed decision on the Artemis II path forward. However, they also acknowledged they may not be able to identify a definitive root cause. As such, engineers are concurrently investigating ways to mitigate the char loss by modifying the heat shield's design or altering Orion's reentry trajectory. No matter the path forward, like with any engineering system, changes to the heat

[15] The Avcoat char is designed to ablate—that is, evaporate or melt from friction with Earth's atmosphere upon reentry.

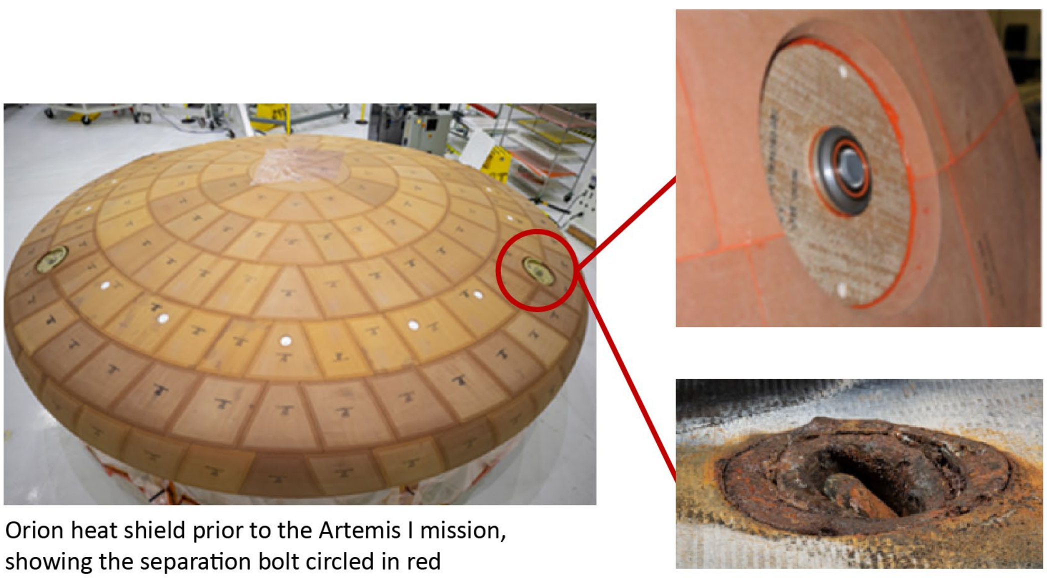
[16] Tiger teams are composed of diverse discipline experts called upon to solve difficult or complex technical problems.

shield design or its operational use can lead to unintended consequences and introduce residual risks.[17] For instance, altering Orion's reentry path can create more stressing conditions that exacerbate the char loss phenomenon or introduce new failures or unknowns into the system. Without understanding the residual effects of introducing design and operational changes, it will be difficult for the Agency to ensure that the mitigations or hardware changes adopted will effectively reduce the risks to astronaut safety.

Bolt Melting and Erosion

Post-flight inspections of the Crew Module/Service Module separation bolts revealed unexpected melting and erosion that created a gap leading to increased heating inside the bolt during Orion's reentry. The Crew Module houses four separation bolts located at specified increments on the capsule to provide structural support for the attachment of the Crew Module to the Service Module. Upon reentry to the Earth's atmosphere, the bolts receive a separation command releasing the Crew Module from the Service Module. The Service Module burns up in Earth's atmosphere, while the Crew Module continues its descent and landing under the protection of the heat shield. As shown in Figure 4, the separation bolts are surrounded by blocks of thermal protective Avcoat and sealed with thermal protective filler, while their surface is exposed to the extreme heat of reentry. NASA requires the bolts to remain flush with the thermal protective material following Service Module separation to guard against excessive heating. However, during Artemis I, three out of the four bolts experienced an exposed gap that allowed for increased heating to the bolt interior and greater than expected melting and erosion.

Figure 4: Orion Crew Module/Service Module Separation Bolt Melting and Erosion



Close up of Orion separation bolt prior to Artemis I mission

Separation bolt melting and erosion post-Artemis I reentry

Orion heat shield prior to the Artemis I mission, showing the separation bolt circled in red

Source: NASA.

Separation bolt melt beyond the thermal barrier during reentry can expose the vehicle to hot gas ingestion behind the heat shield, exceeding Orion's structural limits and resulting in the breakup of the vehicle and loss of crew. Post-flight inspections determined there was a discrepancy in the thermal

[17] Residual risks are the remaining risks that exist after the implementation or exhaustion of all mitigation actions in accordance with a risk management process.

model used to predict the bolts' performance pre-flight. Current predictions using the correct information suggest the bolt melt exceeds the design capability of Orion. While the Agency plans to redesign the separation bolt for later Artemis missions, to mitigate this issue for Artemis II, the Orion Program made minor modifications to the separation bolt design and added additional thermal protective barrier material in the bolt gaps. NASA is also exploring changing the Artemis II mission reentry trajectory to limit friction and heating on the bolts.

Installation of the separation bolt mechanism on the Artemis II Orion vehicle occurred in September 2023. Further testing is ongoing; however, NASA cannot complete final separation bolt assessments until it concludes the investigation on the heat shield char loss in the first half of 2024 and updates its thermal model to account for the full scope of Artemis II design and operational changes. Ultimately, the path forward on the separation bolt melting and erosion condition is dependent on how NASA addresses the unexpected heat shield conditions because any changes to the heat shield Avcoat performance can also impact the bolts' performance. Moreover, like with the heat shield, without understanding the residual effects of introducing design and operational changes, it will be difficult for the Agency to ensure that the mitigations or hardware changes adopted will effectively reduce the risks to astronaut safety.

Uncommanded Power Disruption

Throughout the Artemis I mission, NASA recorded 24 instances of the Power Conditioning and Distribution Unit (PCDU) Latching Current Limiters in the Service Module opening without a documented command.[18] Orion's two PCDUs are responsible for delivering power to the spacecraft's systems, including vehicle propulsion and pressurization. The uncommanded openings are similar to a circuit breaker tripping in a home's electrical panel and disrupting its power. Based on previous ground testing, NASA did not expect to experience any instances of this condition during the mission.

During Artemis I, NASA successfully commanded the opened Latching Current Limiters back to their closed position; however, the PCDU anomalies prevented normal voltages and currents, interrupted the current flow through Orion's Electrical Power System, and failed to deliver power to some of Orion's components during one occurrence. Moreover, the uncommanded openings resulted in a loss of required redundancy for safety-critical systems because only one of two PCDUs were operational during most of the occurrences.

The PCDU investigation team determined radiation was the root cause of the power disruptions. NASA engineers have implemented and tested flight software changes and operational workarounds to help address these power disruption events should they occur during Artemis II. The crew and flight control teams will also receive training on how to respond to these anomalies and return the system to normal functioning. However, without a verified permanent hardware fix addressing the root cause prior to the Artemis II mission, the risk is increased that these systems may not operate as intended, leading to a loss of redundancy, inadequate power, and potential loss of vehicle propulsion and pressurization during the first crewed mission. The Orion Program has accepted this increased risk for Artemis II.

[18] The PCDU is responsible for taking power generated by the solar arrays and distributing it to Orion's systems, including the spacecraft's batteries for periods when the solar arrays are not available due to dark conditions. The Latching Current Limiters are the electronic circuit breakers that control the power from the PCDU to the Service Module components and the rest of the vehicle.

Greater than Expected Launch Damage Necessitates Mobile Launcher 1 Repairs and Improvements

ML-1 Damage

The ML-1 sustained more damage than NASA expected due to the Artemis I launch-induced environment. While NASA anticipated that some materials and equipment would be sacrificial to the launch and require replacement, ML-1 elevators, electrical equipment, enclosure panel doors, and pneumatic tubing sustained significant unexpected damage. The extensive repairs to address this damage will cost more than $26 million, roughly 5 times more than the $5 million the EGS Program originally set aside for post-Artemis I launch repairs.[19]

During launch, the SLS generates exhaust blast plume pressure, random vibration, vibration from acoustics, and heat. These loads—collectively known as the launch-induced environment—can cause damage to the launch vehicle, payload, launch pad, and surrounding structures. NASA's models of how it expected the ML-1 to respond to the Artemis I launch-induced environment underpredicted some of the launch-induced loads—namely horizontal plume pressure, acoustic vibrations, and heat. Loads can have unique and interdependent impacts on a structure. According to NASA officials, acoustics had the biggest impact.

To anticipate the impact of the launch-induced environment on the ML-1, NASA used computer modeling and historical data. NASA focused its acoustic testing on higher frequencies—above 150 hertz (Hz)—and did not record measurements below 20 Hz. As a result, the testing was unable to determine the impact lower frequencies would have on the ML-1. NASA instead relied primarily on Space Shuttle data for the low frequency acoustic estimates, which proved ineffective in predicting the impact of lower frequencies. To this point, according to Agency officials, it was acoustic vibrations at the lower frequencies—specifically between 6 and 8 Hz—that caused the enclosures housing the ML-1 electrical components to open and SLS booster engine corrosive exhaust to penetrate. NASA is working to update all environmental loads analyses with data from the Artemis I launch to refine its predictions for the Artemis II launch.

NASA was able to assess the damage to the ML-1 soon after the launch and has taken steps to make repairs and harden the ML-1 to improve its performance ahead of the Artemis II mission. Repairs to the launch facilities began in January 2023 and are scheduled to continue through May 2024.

Elevators

ML-1 elevator doors were blown off during the Artemis I launch, allowing the interior structure to be heavily damaged. Specifically, the elevator car tracks were bent, and the counterweight was dislodged from the track.[20] It took NASA 6 weeks to bring one elevator back online and roughly 4 months to finish repairing the second elevator. According to an Agency official, going into the Artemis I mission it was not known that the elevator "blast doors" were not in fact blast doors but rather fiberglass doors

[19] While the bulk of the repairs are being made to the ML-1, this amount also includes estimates for post-launch refurbishment of Launch Pad 39B to make repairs to the launch pad's flame trench, chillers, and lighting systems. According to EGS Program officials, the ML-1 repairs have been funded by EGS program reserves.

[20] An elevator counterweight is an added weight that gives balance to the elevator system.

designed to keep wind out. In preparation for Artemis II, the elevator doors will be replaced and frames hardened to meet the requirements of updated loads analyses from the Artemis I mission (see Figure 5).

Figure 5: ML-1 Elevator Damage Post-Artemis I Launch

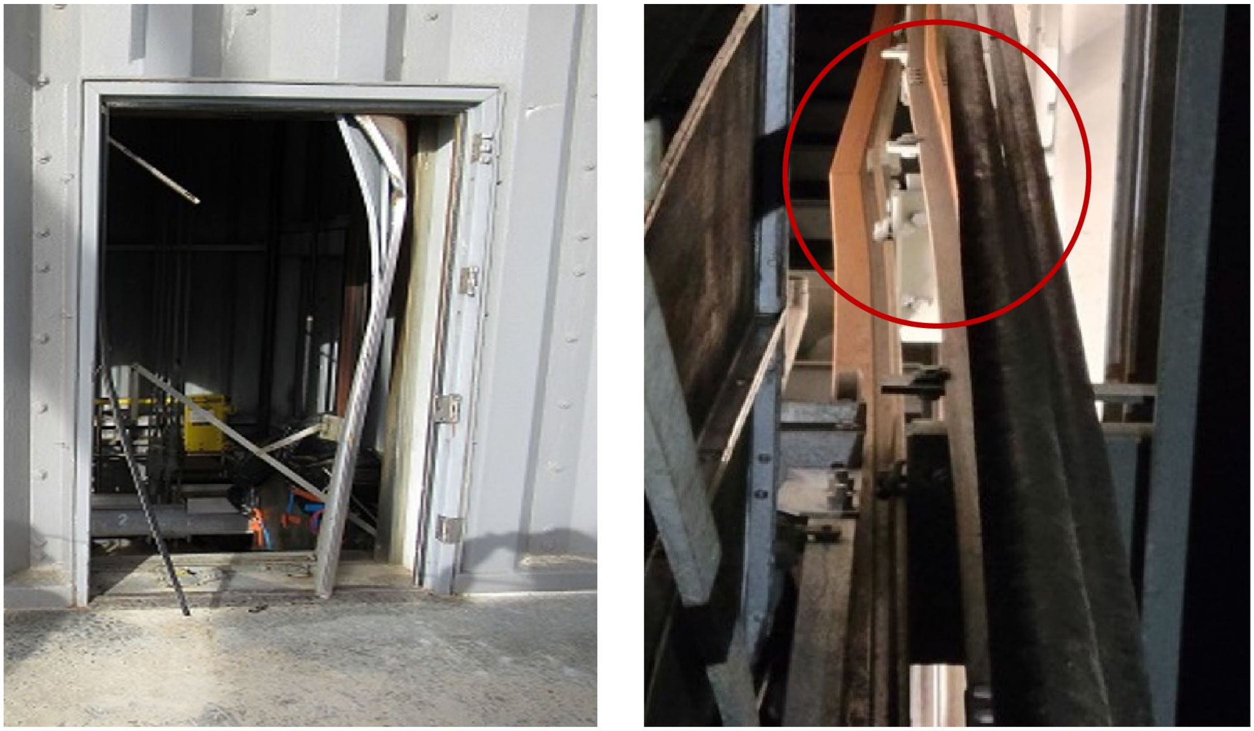


Image on the left shows the damaged elevator doors, while the image on the right shows the bent elevator car tracks (circled in red).

Source: NASA.

Electrical Equipment and Enclosures

In total, 60 enclosures that house ML-1 electrical components sustained damage during the Artemis I launch. Specifically, vibrations caused from low frequency acoustics bent and opened panel doors exposing internal components to corrosive exhaust expelled by the SLS boosters. According to NASA officials, some heritage electrical panels reused on the ML-1 from the Space Shuttle era took heavier damage than other panels due to these panels using a different type of steel that was less resistant to corrosion. Other ML-1 work priorities and the limited availability of steel precluded NASA from replacing these panels prior to the Artemis I launch. In preparation for the Artemis II mission, the Agency plans to add metal strapping around the cabinets to keep the doors shut—an effort that worked to keep other doors closed on the ML-1 (see Figure 6).

Figure 6: ML-1 Panel Door Damage Post-Artemis I Launch

The first image shows bent door latches and the second image shows a bent door that opened during launch

Source: NASA.

Pneumatic Systems

ML-1 base and tower pneumatic systems sustained significant damage during the Artemis I launch resulting in bent, broken, and disconnected tubing.[21] According to NASA officials, some tubing was penetrated by launch debris. Other tubing became disconnected from base pneumatic control panels when welds failed to keep the panel enclosures attached to the launcher base under the acoustics loads created during launch. To mitigate the effects of acoustic vibrations during launch, NASA plans to modify some permanently welded enclosure attachments to spring isolators and change hardline connections to flexhose connections for the base pneumatic panels.

In addition to this damage, nearly all of the 316 stainless steel tubing on the exterior of the ML-1 sustained accelerated corrosion and impingement due to exposure to highly acidic solid rocket booster exhaust, which is expected to continue indefinitely even after cleaning. NASA plans to replace thousands of linear feet of tubing with a variety that is more corrosion resistant. As we reported in October 2023, due to supply chain issues that would have resulted in a 12-week delay, more than half of the tubing being replaced—roughly 10,500 linear feet out of 18,000—has been "borrowed" from the Mobile Launcher 2 construction effort, which did not need the tubing at that time.[22] For the tubing that is not being replaced, the Agency plans to add a special coating to minimize the impacts of corrosive exhaust (see Figure 7).

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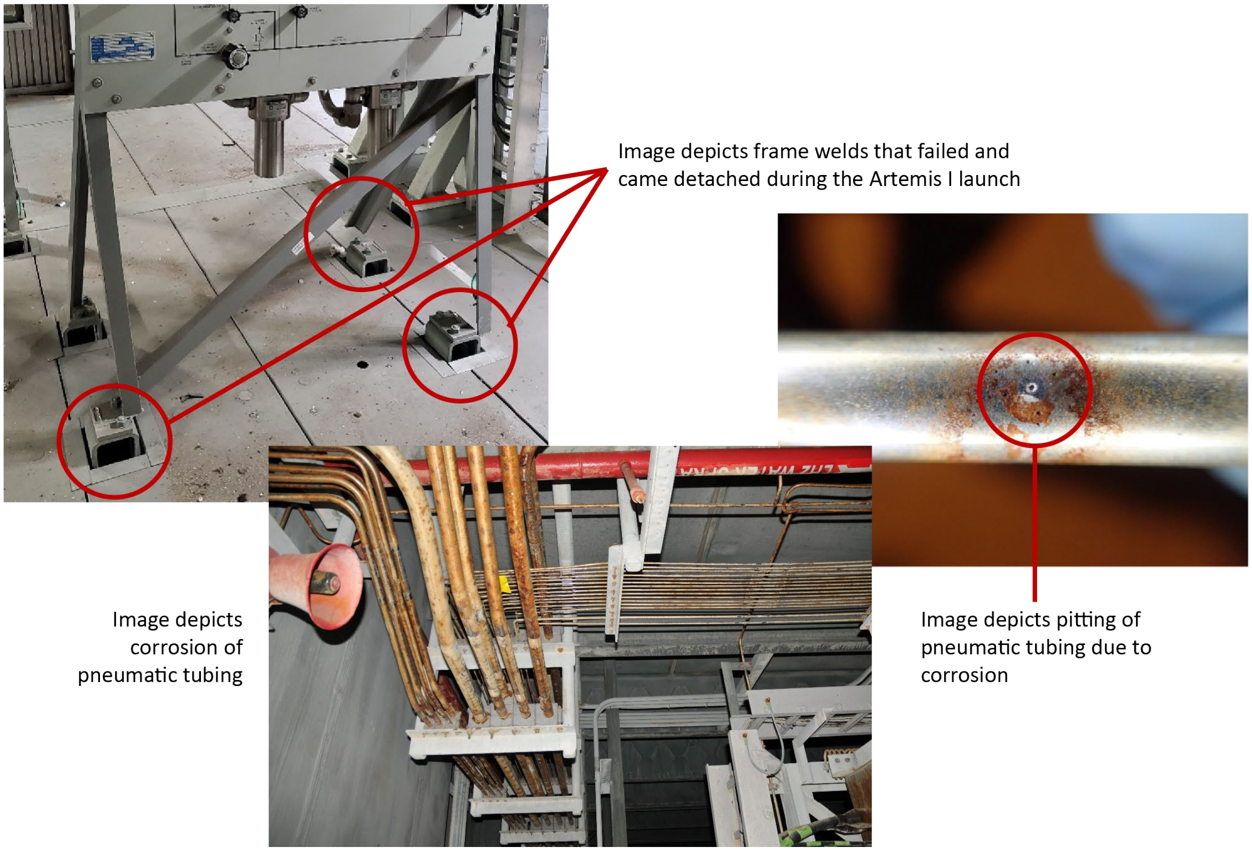
[21] The pneumatic lines supply the launcher and rocket with gaseous nitrogen and helium.

[22] NASA OIG, *NASA's Management of the Artemis Supply Chain* (IG-24-003, October 19, 2023). The ML-1 project purchased the tubing from the Mobile Launcher 2 project for $226,046.

Figure 7: ML-1 Frame Welds and Pneumatic Tubing Post-Artemis I Launch



Source: NASA.

Washdown System

Damage to the gaseous nitrogen supply panel after the Artemis I launch prevented the ML-1's washdown system from working and further exacerbated the damage to the launcher, allowing corrosive exhaust residue from the SLS boosters to coat and slowly corrode ML-1 tubing for days after the launch. The washdown cycle is composed of eight stages that flow for 4 minutes each with a small delay between each stage. Since the system did not work, manual washdowns for the ML-1 started 5 days after launch on November 21, 2022, and did not finish until 11 days later on December 1, 2022. Had the system worked properly, it would have taken 35 minutes to complete the post-launch washdown of the launcher. To correct this problem for the Artemis II mission, NASA is making modifications to prevent damage to the gaseous nitrogen supply panel by replacing the hardline connections with flexhose connections between the facility supply line, vent line, and the panel.

Risk of Debris Strike

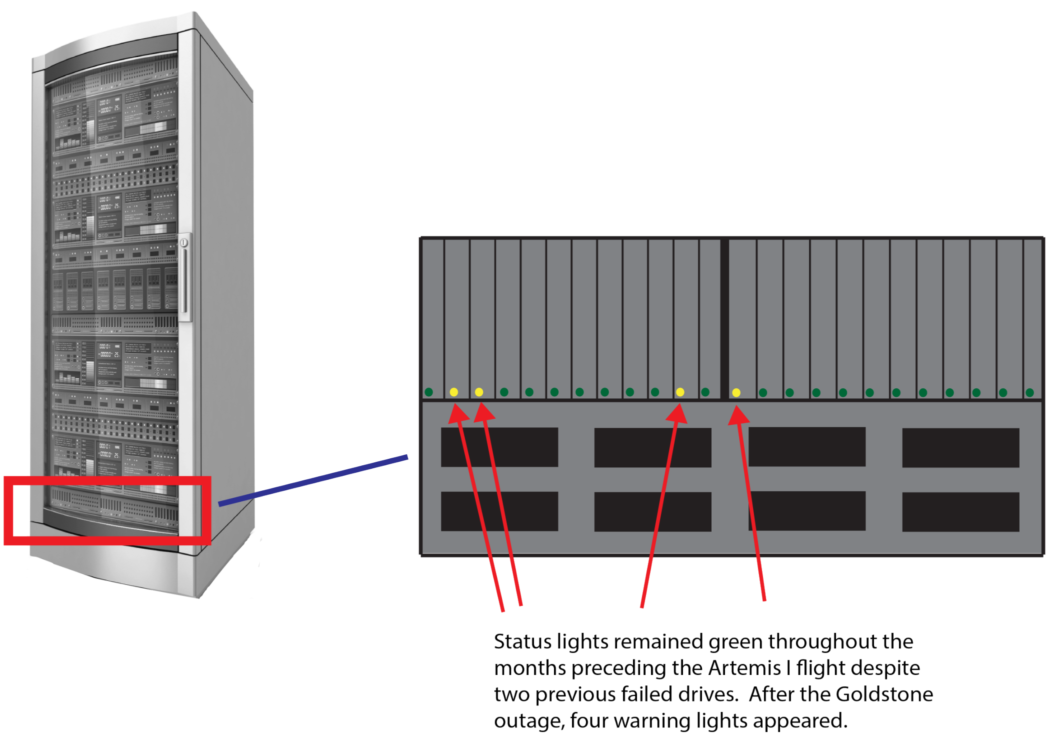
The Artemis I launch generated greater than expected foreign object debris due in large part to the significant amount of damage to the ML-1. For example, one elevator door blown off during the Artemis I launch was captured by the rails on the perimeter of the launch tower, while the other door landed beyond the boundaries of the tower. Debris poses a significant risk of catastrophic damage to vehicle, spacecraft, and critical ground systems. Consequently, in February 2023 the EGS Program stood up a Tiger Team to investigate the issues with launch debris. As of August 2023, the team had identified three primary root causes for the debris issues: (1) launch-induced environment, (2) ML-1 design deficiencies, and (3) process issues. The Tiger Team is developing recommendations to address these issues, including improved models that more accurately reflect the launch-induced environment, redesign of design deficiency nonconformances, and process changes.

In-Flight Communication Losses Underscore the Importance of Maintaining the Deep Space Network

On flight day 18 of Artemis I, NASA encountered a 4.5-hour loss of communications with the Orion spacecraft when one of the three DSN facilities—Goldstone—experienced a site-wide outage. Including Artemis I, a total of 17 NASA and international partner missions were affected with thousands of minutes of telemetry data lost.

Multiple hard drive failures, in combination with an out-of-date operating system, caused the Goldstone outage. The DSN's virtual hosting hardware called the Private Cloud Appliance (PCA) includes 24 hard drives. NASA was relying on the system's internal redundancy, which is designed to withstand up to four hard drives failing. However, the Agency was not aware that two hard drives had already failed over the 12 months preceding the Artemis I mission. Bugs in the out-of-date PCA software prevented failure indicators from operating, including the display of warning hard drive status lights and the automated recovery and system reboot function. Figure 8 depicts a PCA, its 24 hard drives, and where the hard drive status lights are located.

Figure 8: Depiction of DSN Private Cloud Appliance



Source: NASA OIG presentation of Agency information.

The Goldstone communication outage encountered during the Artemis I mission can largely be attributed to network maintenance deferrals and deterioration of hardware, which have been long-standing issues for NASA's DSN. We previously reported that budget reductions challenged DSN's ability to maintain performance levels and threatened future reliability.[23] Specifically, when SCaN reduced DSN's budget in fiscal year 2013, DSN proposed to delay key components of its project to modernize and expand its hardware, reduce personnel at certain locations, and cancel and delay maintenance facility tasks. In fact, the PCAs—deployed in 2016—had only had minor hardware upgrades, leaving them susceptible to software bugs for extended periods of time.

Further compounding the issue is the difficulty DSN officials face in finding time when they can take PCAs offline for maintenance given the increasing demand on the DSN. In July 2023, we reported that DSN is currently operating at capacity, with demand exceeding supply by 40 percent at times.[24] We also reported that demand for DSN support is projected to increase dramatically—by a factor of 10—in the next decade due to the increase in the number of deep space missions and the complexity of human exploration missions. Because each DSN complex relies on a single PCA to host its antenna operations, performing maintenance procedures typically causes operational downtime. Consequently, to maintain network stability prior to and during critical mission phases, such as the months leading up to the Artemis I launch, DSN officials defer maintenance and updates on the PCAs.

NASA has begun to take corrective actions to mitigate the DSN issues that impacted Artemis I communications. In January 2023, SCaN convened a Failure Review Board to investigate the Goldstone outage. Four months later, the Board produced a comprehensive report that included a root cause analysis as well as recommendations. The Board identified weaknesses in NASA's risk assessment and prioritization processes, which should have elevated the PCA to near-term action but instead relied on the hardware's internal redundancy. The Board also recommended that DSN and SCaN work to review existing risks, determine if new risks should be documented, and push for stronger advocacy at the Agency level for additional funding and more frequent operational downtime.

SCaN officials have also taken steps to address the equipment issues and implement process improvements. SCaN replaced the four faulty hard drives that caused the Artemis I Goldstone outage, upgraded the PCA software and operating systems, and pre-staged on-site replacement drives for a quicker recovery should another outage occur. In addition, the Program implemented automated PCA monitoring capabilities, improved the recovery and restart processes, and documented the manual workaround, which brought the system back online.

Further guarding against the potential for an outage during Artemis II, NASA has several new agreements in place with international partners to provide backup coverage should a similar event occur. For example, the Japanese Aerospace Exploration Agency has several antennas in its network, and the European Space Agency has a similar footprint as the DSN. This backup coverage is especially important for NASA's first crewed Artemis mission because, according to the Failure Review Board, the risk of additional drives failing and disrupting communication during the mission is increasingly likely due to the hardware's age. In fact, since the Artemis I mission, two similar failures have occurred at Canberra and Goldstone, requiring the replacement of three additional hard drives. Looking forward, it is critical that the Agency continues to focus on improving DSN's maintenance, operations, and reliability to better ensure the network does not encounter outages that could put the Artemis II crew and spacecraft at risk.

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[23] NASA OIG, *NASA's Management of the Deep Space Network* (IG-15-013, March 26, 2015).

[24] IG-23-016.

Missed Data Collection Opportunities Extend Known Risks to Future Crewed Missions

Artemis I provided NASA the opportunity to test integrated systems in the actual flight environment that Artemis missions will operate. The mission also represented a critical opportunity for known risk reduction ahead of Artemis II. However, limited collection of imagery, telemetry, and physical evidence impacted NASA's ability to fully evaluate and address certain launch, landing, and recovery risks.

Imagery Issues

The Artemis I mission experienced numerous imagery issues during launch, limiting the availability of quality launch imagery data. These issues were further exacerbated by NASA's decision to launch at night. According to Moon to Mars Program Office officials and the Artemis I technical baseline document, daylight launches are highly desired to enhance data collection during key events but are not a requirement.[25] After two unsuccessful daylight launch attempts, NASA determined the program cost and schedule risk associated with waiting for another daytime launch window outweighed the risk of a night launch for Artemis I. The Agency verified and validated camera settings prior to launch as required; however, it did not reverify and revalidate that the camera settings were accurately adjusted for the conditions of a night launch due to lack of procedures.[26] According to Agency officials, software issues caused the cameras to not accept the settings that adjusted for the conditions of the launch environment. As a result, the Artemis I launch experienced exposure issues for 32 of 33 cameras, including under-exposure that resulted in images that were too dark. The mission imagery also saw the field of view slightly out of alignment for six cameras, camera fogginess, and high-speed digital scan lines in images. Should improperly adjusted camera equipment recur on Artemis II, the Agency risks missing detection of critical events that can impact crew and vehicle safety.

SLS Throat Plug Debris

Throat plug debris shown liberating from the SLS booster nozzle during a 2016 ground test. The throat plug—designed to protect the booster before ignition—is rapidly expelled when the booster ignites.

Source: NASA.

Imagery is a key contributor to NASA's ability to identify and collect data necessary to evaluate mission performance. Of primary concern is collecting imagery data on vehicle integrity, attitude and guidance, booster separation, main engine and booster plume effects, and ascent debris releases. For example, a primary flight test objective for Artemis I was to identify liftoff, ascent, and separation debris. Debris impacting the launch vehicle during liftoff and ascent can cause catastrophic damage leading to the loss of mission and ultimately the loss of crew when astronauts are on board. During Artemis I, engineers from NASA's Joint Engineering Team for Imagery described a significant impact to their ability to identify ascent debris due to the dark conditions and improperly

[25] The Mission Definition Baseline, the Artemis I technical document, serves as the central repository for key mission specific requirements and objectives.

[26] NASA GSDO-PLN-1195, Rev. D, *Cross-Program Processes and Agreements for Launch Site Ground Operations* (March 3, 2021).

adjusted camera equipment. For example, engineers could not see the upper two-thirds of the SLS or the debris shedding events from the forward portion of the integrated vehicle. Since debris identification and sizing could not be performed due to the camera issues and the night launch, NASA was unable to close an unresolved SLS booster throat plug debris risk that the Agency has been tracking for more than 10 years.[27]

The EGS Program stood up a Tiger Team in January 2023 to address the technical imagery issues and has already taken some corrective actions. For the exposure issue, EGS is implementing software changes, updating procedure steps, and conducting training. For the field of view issue, corrective actions include making procedural clarifications and updating training. EGS is also adding new verification and validation procedures.[28] Any additional work required to implement these changes could impact the EGS Program's schedule for Artemis II.

Key Hardware Not Recovered

NASA was unable to recover jettisoned hardware from the Orion capsule during Artemis I landing and recovery operations. Of primary importance were recovery of the three main parachutes, which are used to slow the Crew Module for landing to a speed that ensures astronaut safety, and the Forward Bay Cover, which protects Orion's parachutes during the heat of reentry. A failure of any of these systems can lead to crew injuries or fatalities. Orion had an Artemis I flight test objective to demonstrate nominal end-of-mission main parachute and Forward Bay Cover recovery.[29] The Landing and Recovery Team is responsible for recovering the Orion vehicle and crew—along with jettisoned hardware—after splashdown and returning them to land.[30] While the Agency had plans, people, procedures, and hardware in place, the recovery team was not able to arrive at the splashdown location before the jettisoned hardware sank in the Pacific Ocean. Although pre-flight analysis indicated a possibility of enough buoyancy to allow for the recovery forces to arrive in time, the hardware sank faster than projected.

Post-flight inspections of jettisoned hardware allow the Agency to learn more about how the hardware performed, as there is no substitute for the physical assessment of components flown in the actual flight environment. Without recovery and physical inspection of the parachutes and Forward Bay Cover, certain details of their actual performance remain unclear, requiring the Agency to rely on imagery to capture and evaluate as much of the hardware's performance as possible. According to Agency officials, for future missions, the Orion Program is evaluating adding flotation capabilities to the jettisoned hardware to allow additional time for the recovery teams to recover or inspect them for post-flight analysis.

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[27] The SLS booster throat plug is an environmental barrier that prevents heat, dust, and moisture from getting inside the booster before it ignites.

[28] Verification and validation is a testing process during which NASA verifies that a system meets its requirements and validates that a system works as intended.

[29] Recovery of the parachutes and Forward Bay Cover was a secondary flight test objective that the Agency considered desirable but not mandatory. NASA's rationale for recovering jettisoned flight hardware is that it is critical for post-flight engineering analysis.

[30] The interagency Landing and Recovery Team, led by the EGS Program, consists of personnel and assets from the U.S. Department of Defense, including Navy amphibious specialists and Air Force weather specialists, and engineers and technicians from Kennedy Space Center, Johnson Space Center, and the Lockheed Martin Corporation.

Parachutes

NASA could not examine the condition of Orion's three main parachutes because they sank to the bottom of the Pacific Ocean before the recovery team could reach them. Landing is one of the riskiest phases of the mission for astronaut safety. Returning to Earth from lunar orbit at speeds that approach 25,000 miles per hour, the Orion spacecraft relies on its parachutes to slow the vehicle to a safe landing speed of 20 miles per hour or less. Post-flight inspection of parachute hardware can provide important information on flight performance and anomaly resolution, such as debris impact assessments, and can facilitate identification of hardware issues otherwise undetected.

Orion Parachutes During Splashdown

Orion splashing down following the deployment of its main parachutes at the conclusion of the Artemis I mission.

Source: NASA.

NASA performed extensive testing to certify the parachutes prior to Artemis I; however, the Agency was still discovering new findings towards the end of that testing, reinforcing the complexity associated with parachute design, testing, and analytical modeling that predicts flight parachute deployment and performance. The importance of recovering a parachute for analysis was demonstrated in NASA's Commercial Crew Program, which discovered unexpected parachute findings with every crewed mission upon physical inspection of the recovered hardware and imagery. These findings—some of which resulted in design changes—would have gone unidentified without parachute recovery and inspection. Likewise, recovering the Artemis I parachutes would have allowed NASA to inspect and evaluate the potential for debris impact damage as previously discussed.

Forward Bay Cover

After Orion reenters Earth's atmosphere, it jettisons the Forward Bay Cover to allow for the deployment of its parachute system. The Forward Bay Cover jettison operation can lead to parachute line entanglements or recontact with the vehicle, preventing proper parachute deployment and risking crew safety. For Artemis I, predicted jettison loads were higher than the Forward Bay Cover's joint capability, resulting in excessive stress on its fasteners. Overloading the fasteners can potentially lead to their failure, causing the Forward Bay Cover to recontact the Orion capsule after being jettisoned and damage critical flight safety hardware. Without recovery and post-flight inspection of the Forward Bay Cover, details of its actual jettison performance are unclear. Additionally, there was insufficient onboard and external imagery to conduct a performance assessment of key Forward Bay Cover deployment characteristics to determine whether there were any parachute line entanglements or recontact with the spacecraft after jettison.

Inaccessible Data

The Orion Program also struggled to process a portion of the vehicle's telemetry data resulting in a degraded assessment of critical events from the Artemis I mission. Engineers estimate that 20 to 25 percent of Orion's telemetry data will need additional processing to become usable for analysis. This has prevented the Agency from using this data to fully achieve some of its flight test objectives meant to reduce risk for the Artemis II mission. Based on preliminary investigations, engineers believe the information was recorded on the vehicle and exists in a raw format; however, software designed to extract the data from the Orion vehicle and convert it into a usable format is not performing as intended. The Orion Program is still determining the root cause of this issue. Although the inaccessible data prevents the detailed assessment of some measures of performance related to vehicle aerodynamics; mechanisms; and guidance, navigation, and control; Program officials noted that based on the system's overall performance and their review of the available data they are confident the vehicle performed as expected in the flight environment. While the Orion Program continues its Artemis I data recovery efforts and works towards a data processing solution, without a known root cause and implementation of corrective actions, unreadable data may recur on Artemis II, potentially impacting NASA's future risk mitigation efforts as the Artemis missions grow more complex.

Significant Upgrades, Modifications, Testing, and Integration Activities Remain, Delaying the Artemis II Launch Date by Almost One Year

In addition to addressing the technical issues and risks discovered from the Artemis I test flight, NASA has further work and testing that it must complete to safely return humans to lunar orbit. NASA's planned work for Artemis II includes upgrades and modifications to the Orion spacecraft, ground facilities, and SLS rocket. Although NASA is making progress on this work, verification and validation testing for some of these upgrades and modifications is taking longer than expected. Furthermore, qualification and acceptance testing of Orion's component parts uncovered circuitry and battery issues that require additional time to resolve. As a result, in January 2024, NASA announced that it would push the Artemis II launch date from November 2024 to September 2025. While NASA works to address these issues, the Agency will need to balance the timing of stacking all the various components of the SLS and Orion on the ML-1 with the potential for additional delays to correct these and any new issues identified during testing.

NASA Is Making Planned Artemis II Upgrades and Modifications in Support of Adding Crew, but Significant Testing Remains

In support of the Artemis II mission and the addition of crew, NASA is making a variety of planned upgrades and modifications to various Orion, EGS, and SLS systems and facilities. Among the more costly and significant are adjustments to the Orion spacecraft's side hatch, addition of a ground-based Emergency Egress System, and upgrades to the SLS booster separation motor covers. As of January 2024, verification and validation testing of some of these efforts was ongoing. During the verification and validation testing process, NASA verifies that a system meets its requirements and validates that a system works as intended. NASA also identifies and addresses any issues discovered during this process and conducts additional testing as needed. Although NASA is making progress on this work, recent schedules show that more time is needed to test some of the planned upgrades and modifications to the Artemis II systems.

- **Orion Avionics Boxes.** The Orion Program successfully refurbished and installed nine avionics boxes recovered from the Artemis I Orion slated for reuse—an activity the Agency had previously thought would take much longer, be more challenging, and represent the longest path to achieving Artemis II readiness.[31] This effort was completed in February 2023.
- **Orion ECLSS.** Artemis II will be the first flight with the advanced Environmental Control and Life Support System (ECLSS). Key ECLSS components include atmosphere revitalization, pressure control, crew water supply, and crew waste management. NASA previously flew and tested several Orion ECLSS components on the International Space Station. The Artemis II crew will further assess performance of ECLSS capabilities while orbiting Earth to ensure the system is working as expected before committing to the lunar flyby portion of the mission. ECLSS components were installed in multiple stages with the final ECLSS component installed in July 2023. As of January 2024, verification and validation testing was in work, but additional tests are required due to a separate issue with Orion's circuitry that impacts ECLSS functionality.
- **Orion Side Hatch.** The Orion Program is working to address a 7-year-long concern related to the Orion side hatch—the primary entry and exit vehicle path for the crew and ground support personnel prior to launch and after landing. The hatch does not meet pressure opening requirements because it does not have a valve to perform pressure equalization, making it difficult to open manually. This is especially concerning should an emergency require a rapid extraction of the crew while on the launch pad or after splashdown. While methods exist to equalize pressure across the hatch prior to opening, there are some limitations. The Agency is planning to test its emergency egress procedures with the crew to identify any additional required mitigations to address this issue. The scheduled completion date is spring 2024.
- **Ground Environmental Control System.** The EGS Program replaced its Environmental Control System (ECS) with a new one that will provide air supply, thermal control, and pressurization to the integrated Artemis systems while in the Vehicle Assembly Building (VAB). The Program is also making modifications to the ECS at Launch Pad 39B. At a total cost of $60 million, construction of the launch pad ECS was completed in October 2023 and construction of the VAB ECS was completed in December 2023; however, construction issues and resource availability constraints have caused delays to system testing at both the VAB and launch pad.
- **Liquid Hydrogen Sphere.** The EGS Program built a new 1.4-million-gallon liquid hydrogen tank that will supplement the 850,000-gallon tank used during the Artemis I mission. This new, larger tank will enable the Agency to reattempt a launch just 24 hours after a scrub. The EGS Program will complete construction of this project in May 2024 at a cost of $68 million.
- **Emergency Egress System.** The EGS Program constructed a launch pad escape system for flight crew and ground support personnel to evacuate the pad up to a few seconds before launch. The Emergency Egress System will include three platforms on the ML-1 and four baskets. Each of the baskets will have the capability of holding five people. Similar to a zipline, baskets are connected to a slidewire that can transport crew from the ML-1 to the emergency egress landing pad where an armored vehicle will transport them to one of two medical triage sites. The EGS Program was scheduled to complete construction of this system in February 2024 at a cost of $35 million; however, construction issues have delayed the start of testing.

[31] The Orion spacecraft houses a number of state-of-the-art avionics units to handle data generated by onboard systems, control the various functions of the vehicle, carry out commands sent from the ground or crew, and return telemetry data for insight into system status.

- **Emergency Detection System.** The SLS Program installed an autonomous monitoring system that uses the existing network of sensors and data-collecting instrumentation on the rocket to monitor the health of the vehicle systems. If the emergency detection system detects an impending anomaly, it is designed to trigger an abort faster than a human could manually perform, making it a critical element for human space flight. The SLS Program completed this system in June 2023 at a cost of $7.5 million.
- **Booster Separation Motor Covers.** The SLS Program upgraded the booster separation motor covers from aluminum to steel for the Artemis II mission to better protect this vulnerable area against debris impact. Each SLS booster includes 8 booster separation motors—for a total of 16 per launch—that are designed to separate the boosters from the SLS core stage about 2 minutes into flight. Booster separation allows the core stage to continue propelling the vehicle to orbit without the added mass of the fuel-depleted boosters. The SLS Program is scheduled to complete this upgrade in May 2024 at a cost of $1.4 million.

Issues Discovered During Qualification and Acceptance Testing of Key Orion Components Led to Decision to Delay Artemis II

NASA is required to test critical system performance prior to assembling and integrating the SLS and Orion on the ML-1.[32] During qualification and acceptance testing of Orion's circuitry and Crew Module batteries, NASA uncovered hardware defects that increase crew safety risks.[33] Findings from these tests, as well as ongoing work on the heat shield as previously discussed, were in large measure the reasons NASA delayed the Artemis II mission to September 2025.

- **Orion Circuitry Impacts to ECLSS.** In August 2023, the Orion Program uncovered a hardware design deficiency with the circuitry used to command critical components of the Atmosphere Revitalization System, which removes carbon dioxide and trace contaminants from the cabin atmosphere and monitors the composition of the air. Of particular significance, these faulty circuits drive the valves for the removal of carbon dioxide from the crew cabin. The Program deemed this condition unsafe for human space flight because high levels of carbon dioxide can deplete breathable oxygen. As a result, NASA is working to make modifications to the circuitry hardware in difficult-to-access locations inside the assembled Orion spacecraft and perform additional tests to ensure operability.
- **Orion Battery Impacts to Launch Abort.** During functional testing of the Crew Module battery, the Agency identified electrical system performance deficiencies that could limit the four batteries' ability to fully power the spacecraft to landing in the event of an abort, increasing the risk of crew loss. The Orion Program needs to complete a series of tests to determine the accuracy of the abort environments. The investigation into this issue is in the early stages, and NASA has not yet developed a path forward.

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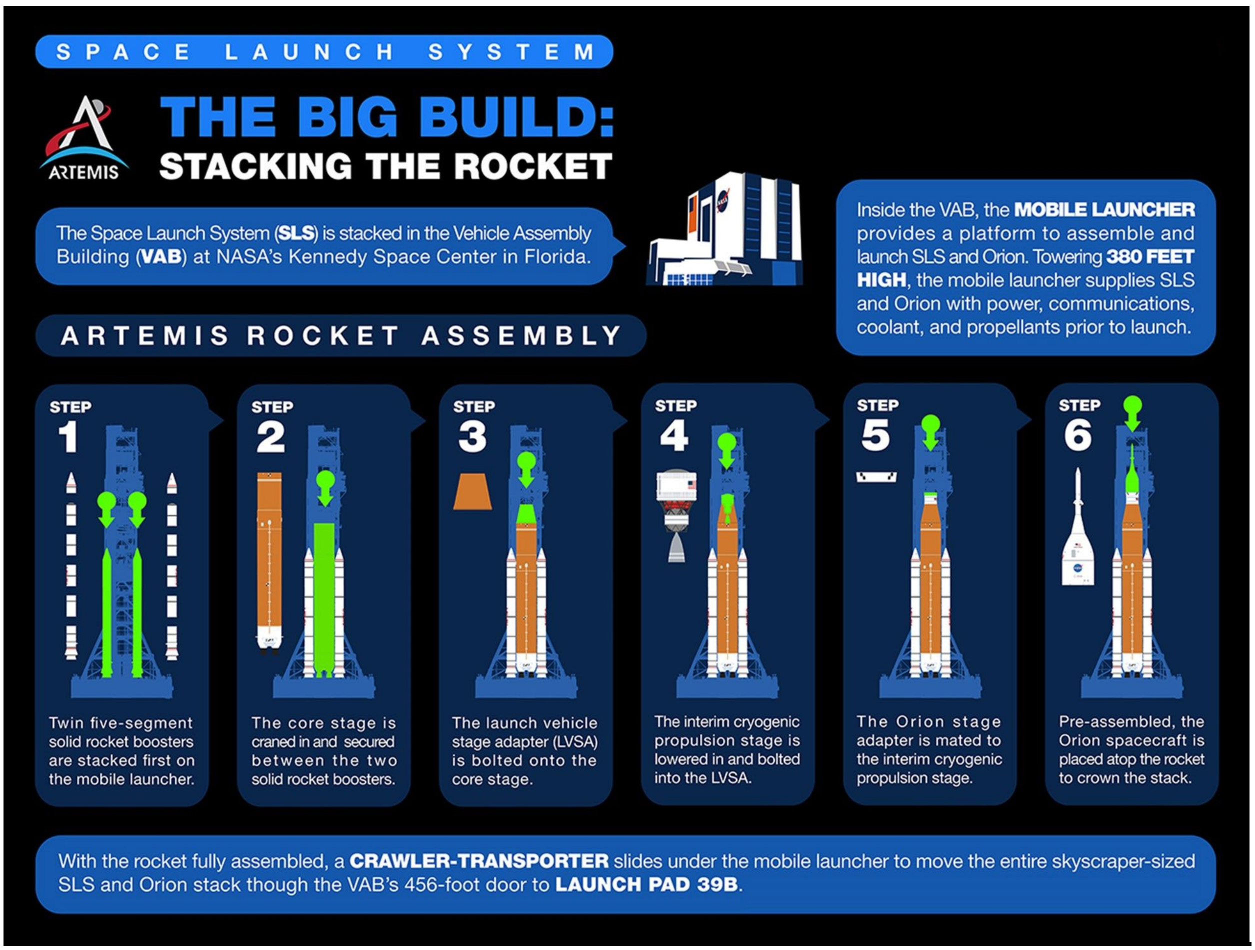
[32] NASA Procedural Requirements 7123.1D, *NASA Systems Engineering Processes and Requirements w/Change 1* (2023).

[33] Qualification testing is a formal test conducted on flight-configured hardware for the purpose of qualifying the product design. Acceptance testing confirms flight hardware performs as qualified and is generally free of defects.

Premature Stacking Could Create Risk of Cost Increases and Additional Schedule Delays

Occurring at the VAB, stacking is the process in which all the various components of the SLS and Orion are integrated on the ML-1. Stacking for the Artemis II mission begins with the SLS boosters, followed by the core stage, launch vehicle stage adapter, Interim Cryogenic Propulsion Stage (ICPS), Orion stage adapter, and umbilical mates. Once these pieces are integrated on the ML-1, EGS will roll the vehicle to the launch pad for integrated testing and a tanking test.[34] After testing, EGS will roll the vehicle back to the VAB, integrate the Artemis II Orion, and conduct additional integrated testing. See Figure 9 for a depiction of the Artemis stacking process.

Figure 9: Artemis Stacking Process

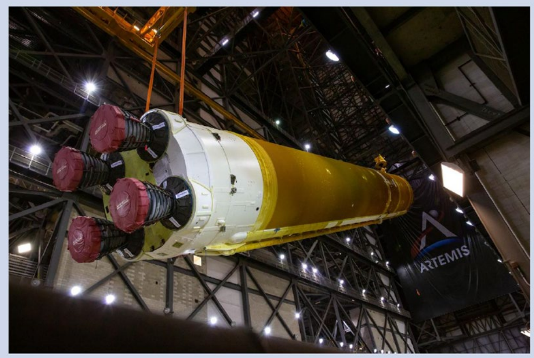


Source: NASA.

[34] During tanking operations, teams will load the SLS rocket with liquid oxygen and liquid hydrogen, beginning with the rocket's core stage and then the ICPS.

Once stacking of the integrated systems begins, NASA must carefully monitor and track key Artemis II hardware that has a limited operating life before it must be serviced or replaced. In particular, the SLS solid rocket boosters—the first element in the stacking process—have a life of 12 months once stacked in their upright position on the ML-1 in the VAB.[35] However, there are options to extend the stack life of the boosters. For the Artemis I mission, although booster stacking began in November 2020, the Agency was able to extend the booster stack life to accommodate a November 2022 launch. The ability to extend booster stack life is based on actual hardware measurements of each individual booster. As such, there is no guarantee that the life of the boosters for the Artemis II mission can be extended the same amount of time as the Artemis I mission. Premature stacking of the Artemis II boosters could exhaust their usable life requiring their replacement—a costly and time-consuming effort.

Artemis I Stacking



The SLS core stage being raised in the Vehicle Assembly Building for stacking of the Artemis I rocket.

Source: NASA.

Unresolved issues from the Artemis I mission increase the risk of delays that could put booster stack life in jeopardy if NASA begins stacking before it fully understands the extent to which system and operational modifications are required for Artemis II. For example, NASA has not yet established a course of action and schedule to address Orion anomalies that must be mitigated before Artemis II. As discussed previously, the Artemis I test flight revealed unexpected Orion heat shield char loss, separation bolt melting and erosion, and power disruptions that require mitigation. If the Agency determines it needs to make a hardware design change on a system after it begins stacking, unstacking could be costly and time consuming, especially if the time to complete a hardware modification outruns the limited lifespan of stacked systems. Moreover, NASA requires complete system-level verification and validation testing before assembly and integration with other systems.[36] As components undergo testing to confirm their functionality, there is a risk of delays should issues arise, as evidenced by NASA's decision to delay Artemis II to address Orion life support system circuitry and Crew Module battery issues discovered during recent testing. While NASA's decision to push back the Artemis II launch date will provide the Agency with more time to prepare for the first crewed mission, NASA will need to appropriately balance its time frame for corrective actions with the start of stacking.

[35] The SLS, Orion, and EGS programs are responsible for identifying, monitoring, and tracking key Artemis II limited operating life items (LOLI). LOLIs are time- or usage-based limitations on hardware that must be carefully monitored to ensure the useful life does not expire and become a threat to processing or mission success. The top three LOLIs that could have the biggest impact on Artemis II are (1) battery life; (2) the number of rollouts of the vehicle to the pad, for which the limit is seven; and (3) booster stack life.

[36] NASA Procedural Requirements 7123.1D.

CONCLUSION

Safely returning humans to and from lunar orbit presents a set of unique challenges and risks that NASA has not faced since the Apollo era. The Artemis II mission will serve as NASA's first crewed test flight of the integrated SLS, Orion, and ground systems and will include the first-time use of numerous critical elements that will provide support to the crew both during launch and the mission. NASA utilizes flight tests to examine how systems perform in their intended environment allowing the Agency to confidently mitigate risks, certify system designs, and validate mission capabilities. While NASA officials consider Artemis I an overall success, providing important data and lessons learned, the mission also revealed significant technical issues that the Agency needs to address ahead of Artemis II. Most importantly, identifying and mitigating the root cause of the Orion heat shield and separation bolt melting and erosion issues will be crucial for the Agency moving forward.

To its credit, NASA management has expressed a commitment to understanding the root cause of the heat shield char loss prior to the Artemis II launch. Moreover, the Agency is taking appropriate action to address other issues that impact its launch readiness, including upgrades and modifications required to support the addition of crew and testing and integration of the SLS, Orion, and ML-1. Moving the Artemis II launch date to September 2025 allows the Agency additional time to investigate the Orion heat shield and address newly discovered issues involving Orion's circuitry and Crew Module batteries. As NASA proceeds with preparation and system assembly for the Artemis II launch, any decisions regarding how to mitigate Artemis I issues will need to be weighed against the ability to modify, remove, or replace at-risk hardware if needed after stacking begins.

Human space flight by its very nature is inherently risky, and the Artemis campaign is no exception. We urge NASA leadership to continue balancing the achievement of its mission objectives and schedule with prioritizing the safety of its astronauts and to take the time needed to avoid any undue risk.

RECOMMENDATIONS

To ensure the safety of the crewed Artemis II mission, we recommended the Associate Administrator for Exploration Systems Development Mission Directorate:

1. Ensure the root cause of Orion heat shield char liberation is well understood prior to launch of the Artemis II mission.
2. Conduct analysis of Orion separation bolts using updated models that account for char loss, design modifications, and operational changes to Orion prior to launch of the Artemis II mission.
3. Require EGS conduct additional verification and validation for launch imagery equipment prior to launch attempts should launch conditions change.
4. Reexamine procedures to better ensure recovery of Orion jettisoned hardware for the Artemis II mission.
5. Develop a corrective action plan to mitigate or prevent the recurrence of uninterpretable Orion telemetry data for the Artemis II mission.
6. Establish a course of action and timeline for individual Artemis system design changes before beginning integrated system assembly stacking operations.

We provided a draft of this report to NASA management who concurred with our recommendations and described planned actions. We consider the proposed actions responsive and will close the recommendations upon completion and verification. While the Agency noted that its planned actions have been completed for Recommendations 4, 5 and 6, we were not provided evidence of these actions prior to issuance of this report.

In addition to responding to the recommendations, the Agency provided comments on several concerns it had with the audit. First, the Agency noted that "the report's tone might suggest that the OIG [Office of Inspector General] identified the risks discussed, when in fact, all recommendations were already being addressed by NASA through forward risk-based disposition prior to the audit." We agree NASA had identified most of the risks we discuss in this report, and we noted that the Agency is taking appropriate action to support the addition of crew and testing and integration of the SLS, Orion, and ML-1. Nonetheless, final and definitive mitigation actions on these risks had not been completed at the time of our reporting. In our judgment, completing these recommendations would better ensure the safety of the crewed Artemis II mission.

Second, the Agency questioned the OIG's role and qualifications in making what it characterizes as "engineering recommendations." The Agency further noted that "combining the roles of auditing and engineering recommendations could result in conflicts of interest, compromise the integrity of existing safety processes, and potentially decouple objective risk management in ongoing engineering development." We disagree. Providing timely recommendations aimed at further ensuring the safety of astronauts in the upcoming Artemis II mission is not only well within the oversight role of the OIG but is a vital responsibility of our office. We will continue to provide the level of oversight of the Artemis campaign that we deem appropriate. That said, it is not our intention, nor have we attempted, to replace the technical expertise of qualified individuals within ESDMD or the technical authority organizations which are staffed with experienced engineering and science professionals. Our analysis relies on the documents and testimony of ESDMD officials and those from technical authority organizations.

Third, the Agency noted its "objective to cooperate fully and provide OIG with access to information and documentation relevant to their audits, evaluations, and investigations" as well as the time and effort spent responding to activities associated with this audit. We appreciate ESDMD's efforts in supporting our work, and we were generally provided what we needed to complete the audit. Nonetheless, we believe more efficient access to requested information would have significantly reduced the workload for both the OIG and the Agency.

The Artemis campaign is NASA's most high-profile ongoing activity involving both extraordinary costs as well as missions that by their very nature put humans at risk. Given the high stakes, NASA OIG will continue to exercise its statutory oversight role to increase the transparency of Artemis activities by providing independent and objective analysis and information to the Agency, Congress, and the public. Looking forward, we will continue to work with NASA in balancing the effort to support our oversight role with the Agency's important work in ensuring the success of the Artemis campaign.

Major contributors to this report include Ridge Bowman, Human Exploration Audits Director; Deanna Lee, Assistant Director; Kelsey Dalton; Antonia Islas; Sarah McGrath; and Dimitra Tsamis. Additionally, Amanda Perry provided editorial and graphics support, Cody Bryant provided data analytics support, and Shani Dennis provided legal support.

If you have questions about this report or wish to comment on the quality or usefulness of this report, contact Laurence Hawkins, Audit Operations and Quality Assurance Director, at 202-358-1543 or laurence.b.hawkins@nasa.gov.

George A. Scott

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George A. Scott
Acting Inspector General

Appendix A: Scope and Methodology

We performed this audit from February 2023 through February 2024 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objective. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objective.

In this report we examined NASA's readiness for the Artemis II mission. To accomplish our objective, we conducted interviews and had discussions with officials at NASA Headquarters, Marshall Space Flight Center, and Johnson Space Center. Additionally, we conducted a site visit at Kennedy Space Center to speak with program officials and observe post-Artemis I damage to ground facilities and preparations in place for Artemis II.

To determine the extent to which NASA met its Artemis I objectives, we reviewed key documents to evaluate mission performance as well as NASA's mission coverage and preliminary flight reviews. Additionally, we assessed NASA's progress towards its Artemis I Post-Flight Assessment Review (PFAR) and knowledge capture efforts. We did not review the Artemis I PFAR because some information within the review was not yet finalized or reviewed by NASA management. As such, there may be other risks regarding Artemis II readiness not identified within this report. However, to assess Artemis I mission performance, we interviewed officials from ESDMD; the SLS, Orion, EGS, and SCaN programs; and other internal and external technical experts and stakeholders from the Office of Safety and Mission Assurance, Flight Operations Directorate, and the Aerospace Safety Advisory Panel.

To assess the Agency's progress towards Artemis II, we examined each of the deep space exploration systems' performance reviews, planned schedules, risk analyses, mission integration reviews, and quarterly program reviews. We also visited Kennedy Space Center and observed the impact of Artemis I on launch facilities and the status of repairs, modifications, and upgrades to ground systems. Additionally, we had discussions and interviewed members of the Office of Safety and Mission Assurance, Office of the Chief Medical Officer, and the Aerospace Safety Advisory Panel to gain insight into safety risks.

Assessment of Data Reliability

We did not use computer-processed data to perform this audit.

Review of Internal Controls

We assessed internal controls and compliance with requirements related to the Artemis campaign's first two missions. Control weaknesses are identified and discussed in this report. However, because our review was limited to these internal control components and underlying principles and further limited by our inability to assess the Artemis I PFAR, it may not have captured all internal control deficiencies that existed at the time of this audit. Our recommendations, if implemented, will improve the identified control weaknesses.

Prior Coverage

During the last 5 years, the NASA OIG and Government Accountability Office have issued 14 reports of significant relevance to the subject of this report; they can be accessed at https://oig.nasa.gov/audits/auditReports.html and https://www.gao.gov.

NASA Office of Inspector General

NASA's Management of the Artemis Supply Chain (IG-24-003, October 19, 2023)

Audit of NASA's Deep Space Network (IG-23-016, July 12, 2023)

NASA's Management of the Space Launch System Booster and Engine Contracts (IG-23-015, May 25, 2023)

NASA's Management of the Mobile Launcher 2 Contract (IG-22-012, June 9, 2022)

*NASA's Management of the Artemis Missions (*IG-22-003, November 15, 2021)

*Artemis Status Update (*IG-21-018, April 19, 2021)

NASA's Management of the Orion Multi-Purpose Crew Vehicle Program (IG-20-018, July 16, 2020)

Audit of NASA's Development of Its Mobile Launchers (IG-20-013, March 17, 2020)

NASA's Management of Space Launch System Program Costs and Contracts (IG-20-012, March 10, 2020)

Government Accountability Office

Space Launch System: Cost Transparency Needed to Monitor Program Affordability (GAO-23-105609, September 7, 2023)

NASA Lunar Programs: Improved Mission Guidance Needed as Artemis Complexity Grows (GAO-22-105323, September 8, 2022)

NASA Lunar Programs: Moon Landing Plans Are Advancing but Challenges Remain (GAO-22-105533, March 1, 2022)

NASA Human Space Exploration: Significant Investments in Future Capabilities Require Strengthened Management Oversight (GAO-21-105, December 15, 2020)

NASA Human Space Exploration: Persistent Delays and Cost Growth Reinforce Concerns over Management of Programs (GAO-19-377, June 19, 2019)

Appendix B: Management's Comments

National Aeronautics and Space Administration

Mary W. Jackson NASA Headquarters
Washington, DC 20546-0001

Reply to Attn of: Exploration Systems Development Mission Directorate

TO: Assistant Inspector General for Audits

FROM: Associate Administrator for Exploration Systems Development Mission Directorate

SUBJECT: Agency Response to OIG Draft Report, "NASA's Readiness for the Artemis II Crewed Mission to Lunar Orbit" (A-23-07-00-HED)

The National Aeronautics and Space Administration (NASA) appreciates the opportunity to review and comment on the Office of Inspector General (OIG) draft report entitled, "NASA's Readiness for the Artemis II Crewed Mission to Lunar Orbit" (A-23-07-00-HED), dated March 13, 2024.

The anticipation surrounding Artemis II reflects the excitement, innovation, and collaborative spirit driving NASA's ambitious goals for the future of space exploration. The Artemis II mission represents a significant milestone in NASA's Artemis campaign and human space exploration efforts, bringing us one step closer to returning humans to the Moon and ultimately sending astronauts to Mars. NASA remains unwaveringly committed to ensuring safe missions to the Moon, reflecting its dedication to the safety of astronauts, mission success, and the advancement of human space exploration. The Exploration Systems Development Mission Directorate (ESDMD) continuously learns from past missions and incorporates lessons learned into future missions to enhance safety and performance. Through post-mission analyses, assessments, and feedback mechanisms, ESDMD identifies areas for improvement and implements corrective actions to optimize mission safety and effectiveness.

ESDMD recognizes the critical role the OIG plays in evaluating whether there are instances of waste, fraud, or abuse in the Federal Government. ESDMD is fully committed to transparency and accountability. It is ESDMD's objective to cooperate fully and provide OIG with access to information and documentation relevant to their audits, evaluations, and investigations. During this audit, ESDMD provided 617 products, attended eight requested meetings, and conducted 17 hours of interviews. Altogether, this activity recorded an estimated 700-725 hours of work from our ESDMD team. This commitment to transparency underscores our dedication to upholding the highest standards of integrity and ethics in all aspects of our work.

Being audited in the middle of a development process presents several challenges including disruptions to ongoing workflow and priorities due to the reallocation of resources and the coordination challenges associated with audit activities. The dynamic nature of development means that changes can occur rapidly, making it challenging to update information for audit requirements that are based on a snapshot of the project at a specific point in time.

The Artemis I flight was designed as an uncrewed test to identify issues which might occur in the integrated nature of this complex system that modeling or ground testing could not predict. NASA expected to discover and resolve issues before Artemis II. This process of finding and addressing engineering challenges is a natural part of the design-test-fix process. NASA is concerned that the report's tone might suggest that the OIG identified the risks discussed, when in fact, all recommendations were already being addressed by NASA through forward risk-based disposition prior to the audit.

NASA will continue to identify, assess, prioritize, and mitigate risks to maximize success. While it is ESDMD's understanding that the primary role of this audit was to assess and ensure compliance with established standards, regulations, and best practices, ESDMD observes this report and its recommendations to be more engineering focused than having a scope of understanding our risk management. ESDMD is focused on ensuring that informed engineering recommendations are provided by experienced individuals or teams with specialized engineering knowledge and a comprehensive understanding of the development context and risk trades. There is a concern that combining the roles of auditing and engineering recommendations could result in conflicts of interest, compromise the integrity of existing safety processes, and potentially decouple objective risk management in ongoing engineering development. Furthermore, the Agency allocates resources to technical authority organizations (including the Offices of the Chief Engineer and Safety and Mission Assurance) in addition to a Congressionally mandated Aerospace Safety Advisory Panel, both of which are staffed with experienced engineering and science professionals.

ESDMD recognizes the importance of the certification process and continues to emphasize safety, reliability, and mission success, with a focus on mitigating risks and ensuring the well-being of astronauts and personnel involved in spaceflight missions. ESDMD would highlight that some of the recommendations listed in this report are considered outside of the certification process. ESDMD and NASA are committed to ensuring the balance of risk management processes across all programs.

In the draft report, OIG makes six recommendations to NASA designed to ensure the safety of its lunar programs, including the Artemis II mission scheduled for September 2025. ESDMD would like to emphasize that all these recommendations were already being assessed in accordance with expectations documented in Exploration Systems Development Mission Integration Implementation Plan, Artemis I Post Flight Analysis Review (PFAR) Plan prior to the audit.

Specifically, the OIG recommends the Associate Administrator for ESDMD:

Recommendation 1: Ensure the root cause of Orion heat shield char liberation is well understood prior to launch of the Artemis II mission.

Management's Response: NASA concurs. Testing the heatshield performance was a key goal of the Artemis I flight. Evaluation of the heatshield's performance, as well as the development of a root cause analysis and a plan for moving forward, had already begun before the start of the audit. NASA continues to make significant progress evaluating the root cause of the heatshield char loss. Ground testing successfully recreated char loss in the arc jet facility using large-scale test panels of full-size Avcoat blocks. The recreated char loss has the same features as observed on the Artemis I heat shield. The team is currently synthesizing the test results together with the leading theory for root cause and are planning formal presentations to the necessary technical forums in preparation for a recommendation to the Orion Program Control Board for Artemis II in April/May timeframe. The recommendation will include Artemis II heat shield operational capabilities based on the latest thermal analysis work. An Independent Review Team effort planned for May 2024 will confirm the team's recommendations to the program on the root cause, heat shield capability, and corrective actions going forward.

Estimated Completion Date: June 30, 2024

Recommendation 2: Conduct analysis of Orion separation bolts using updated models that account for char loss, design modifications, and operational changes to Orion prior to launch of the Artemis II mission.

Management's Response: NASA concurs. Evaluation of the separation bolts' performance, along with the development of a root cause analysis and a plan for future actions, had already commenced prior to the audit. The Orion Program is currently conducting analysis using updated models based on the findings of the heat shield char liberation investigation team. This analytical work is on track to be completed before the Artemis II mission.

Estimated Completion Date: June 30, 2024

Recommendation 3: Require Exploration Ground Systems (EGS) conduct additional verification and validation for launch imagery equipment prior to launch attempts should launch conditions change.

Management's Response: NASA concurs. By conducting the Artemis I test flight, NASA gathered valuable data and experience that will help improve the design and operation of the Artemis II spacecraft and ultimately enhance the success of future missions. Per EGS's standard requirements and processes, verification and validation activities are conducted prior to an operation to ensure the configuration is understood, that it meets the requirements, and that the system performs as intended by the user. As part of the Artemis I Imagery Deficiency Tiger Team, which was initiated in January 2023, prior to this audit, EGS has identified and is implementing corrective actions including camera control software enhancements, procedural updates, testing approaches, and workforce training and certification improvements. The launch imagery software, procedures, and personnel will be exercised and proven through Artemis II preparation events to include Mobile Launcher (ML)/Pad Ignition Overpressure Protection and Sound Suppression and Fire Suppression System Launch Cooling Test Integrated System Verification and Validation (ISVV-2), ML/Pad Imagery Demonstration (ISVV-6), and the Artemis II Tanking Test.

Estimated Completion Date: September 30, 2024

Recommendation 4: Reexamine procedures to better ensure recovery of Orion jettisoned hardware for the Artemis II mission.

Management's Response: NASA concurs. NASA conducted the Artemis I test flight to ensure the safety, reliability, and performance of its spacecraft and systems. This test flight allowed NASA to identify and mitigate potential issues that may arise during actual missions. Concurrence is based on the action of utilizing the Agency's process of conducting a PFAR of Artemis I, which was conducted prior to this audit report. Both the Orion and EGS programs have determined that the plans and procedures of the EGS Recovery Team are accurate and Orion requirements have been revised to clarify the requirements for jettison hardware recovery. If the hardware does not sink before recovery forces arrive on-site, the recovery team will make every effort to recover the hardware. The Orion program will assess whether flotation capability needs to be added for future missions to assist in recovery.

Estimated Completion Date: Completed

Recommendation 5: Develop a corrective action plan to mitigate or prevent the recurrence of uninterpretable Orion telemetry data for the Artemis II mission.

Management's Response: NASA concurs. This action has already been implemented. The Orion Program submitted a corrective action plan on February 17, 2024, to the OIG indicating that this recommendation can be closed.

Estimated Completion Date: Completed

Recommendation 6: Establish a course of action and timeline for individual Artemis system design changes before beginning integrated system assembly stacking operations.

Management's Response: NASA concurs. This action is already being implemented as part of normal processes and can be closed. The Moon to Mars Program (M2M) routinely monitors the progress of Artemis II hardware and software, including the status of system design changes, verification and validation testing, necessary operational modifications, and resolutions for any anomalies. Each individual system design change for Artemis II will undergo a design certification process, culminating in design certification reviews at the program level (Orion, Space Launch System, EGS).

Additionally, M2M will conduct a design certification review for the integrated system. As Artemis II stacking is currently projected to commence before the completion of the design certification reviews, M2M will conduct a checkpoint before the start of Artemis II stacking. This checkpoint will evaluate the status of hardware and software across M2M, including design changes, verification and validation testing, operational changes, anomaly resolutions, and limited life items. It will determine if M2M is prepared to begin stacking operations, considering any ongoing work, and outstanding risks. After the integrated system design certification review, M2M will conduct the Artemis II operational readiness review and proceed with the flight certification process.

Estimated Completion Date: Completed

NASA is dedicated to continuous enhancement of our processes and procedures to ensure safety and address potential risks and deficiencies. However, the redundancy in the above recommendations does not help to ensure whether NASA's programs are organized, managed, and implemented economically, effectively, and efficiently.

NASA remains committed to flying safely and looks forward to a successful Artemis II mission that continues to push the boundaries of human achievement, scientific discovery, and the advancement of space exploration.

We have reviewed the draft report for information that should not be publicly released. As a result of this review, we have not identified any information that should not be publicly released.

Once again, thank you for the opportunity to review and comment on the subject draft report. If you have any questions or require additional information regarding this response, please contact Christine Solga at (202) 358-1238.

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Catherine Koerner
Associate Administrator for Exploration Systems Development
Mission Directorate

Appendix C: Report Distribution

National Aeronautics and Space Administration

Administrator
Deputy Administrator
Associate Administrator
Chief of Staff
Associate Administrator for Exploration Systems Development Mission Directorate
Associate Administrator for Space Operations Mission Directorate
Moon to Mars Program Manager
Exploration Ground Systems Program Manager
Orion Multi-Purpose Crew Vehicle Program Manager
Space Launch System Program Manager
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Non-NASA Organizations and Individuals

Office of Management and Budget
  Deputy Associate Director, Climate, Energy, Environment and Science Division

Government Accountability Office
  Director, Contracting and National Security Acquisitions

Congressional Committees and Subcommittees, Chairman and Ranking Member

Senate Committee on Appropriations
  Subcommittee on Commerce, Justice, Science, and Related Agencies

Senate Committee on Commerce, Science, and Transportation
  Subcommittee on Space and Science

Senate Committee on Homeland Security and Governmental Affairs

House Committee on Appropriations
  Subcommittee on Commerce, Justice, Science, and Related Agencies

House Committee on Oversight and Accountability
  Subcommittee on Government Operations and the Federal Workforce

House Committee on Science, Space, and Technology
  Subcommittee on Investigations and Oversight
  Subcommittee on Space and Aeronautics

(Assignment No. A-23-07-00-HED)