Implementation Plan for a NASA Integrated Lunar Science Strategy in the Artemis Era

November 2024

Cover image: The “Cobra head” volcanic vent fed a river of lava that flowed down the Aristatuchus plateau before spilling out onto the lava plains of Oceanus Procellarum. To the east (left) of the Cobra head is Aristarchus crater and to the west (right) is Herodotus crater; Marius crater (40 kilometer diameter) is in the far distance very near the limb.
Apollo 15 Metric Photograph AS15-M-2610.

Image Credit: NASA

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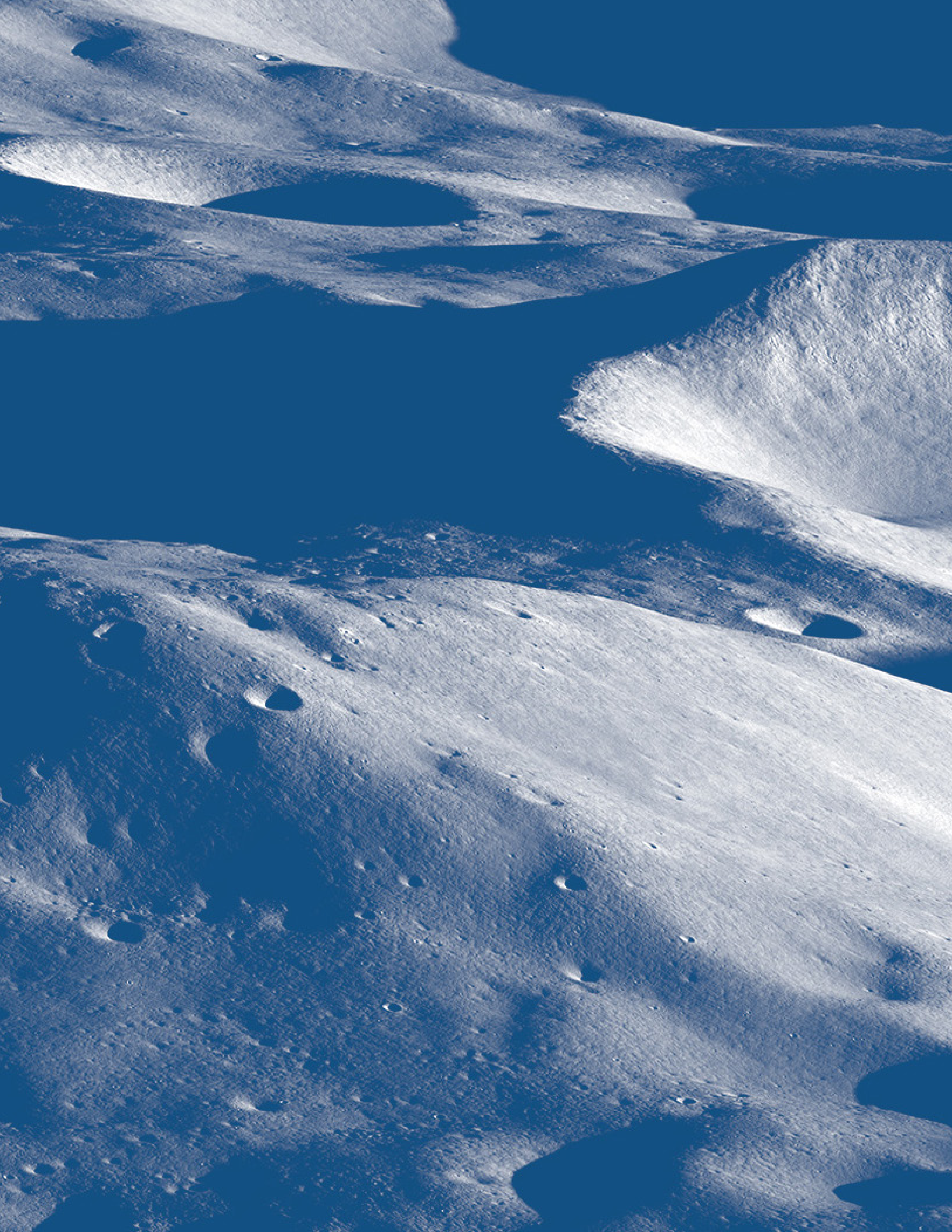

Executive Summary

This is an exciting time for lunar science and exploration. We are driving revolutionary change in our understanding of the Moon and our solar system by leveraging a range of technologies and capabilities that have never-before been possible.

Lunar science and exploration are ubiquitous throughout the recent Decadal Survey in Planetary Science Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032 (OWL)—demonstrating that the Moon is a vital cornerstone of planetary science and exploration. In parallel with the Decadal Survey, NASA recently delivered its Moon to Mars Strategy and Objectives to guide NASA's exploration strategy encompassing the return of astronauts to the Moon, sustained lunar science and exploration, and to crewed landings on Mars. Among the four Lunar and Planetary Science (LPS) objectives, there are three lunar science objectives, which draw directly from the science themes of the Decadal Survey:

Science Theme 1 Uncover the lunar record of solar system origin and early history.	→	**LPS-1** Uncover the record of solar system origin and early history.
Science Theme 2 Understand the geologic processes that shaped the early Earth that are best preserved on the Moon.	→	**LPS-2** Advance understanding of the geologic processes that affect planetary bodies.
Science Theme 3 Reveal inner solar system volatile origin and delivery processes.	→	**LPS-3** Reveal inner solar system volatile origin and delivery processes.

This Implementation Plan provides a snapshot of NASA's plans to implement the strategy recommended in OWL and to address the M2M objectives relevant to lunar science. The word "integrated" in the title refers to integrating the capabilities and new opportunities afforded by Artemis and CLPS alongside more traditional mechanisms such as The Discovery and New Frontiers Programs and various Research and Analysis (R&A) elements to achieve our lunar science objectives. It is an opportunity to present the full scope of tools currently available to NASA and how they map to high-priority lunar science that can be accomplished on and at the Moon. It is also an opportunity to build a plan for future NASA-led, lunar-focused science and exploration activities that is flexible and can be adapted to a changing landscape (i.e., capability growth, priority evolution, and budgetary fluctuation).

Based on decadal priorities and other community documents, this implementation plan has identified the six biggest lunar science challenges, i.e., those whose implementation necessarily requires a strategy in order to achieve. These challenges are:

- South Pole-Aitken (SPA) Basin Sample Return
- Lunar Geophysical Network
- Cryogenic Volatile Sample Return
- Lunar Chronology
- Lunar Formation and Evolution
- Lunar Volatiles

The objectives of each of these big challenges can be addressed through various architecture options, including competed or directed missions, CLPS, and/or Artemis. In addition to those architecture options, there is a wide range of lunar science supporting infrastructure that also allows progress to be made towards NASA's lunar science objectives.

Although this document focuses largely on the science of the Moon, exploration on and at the Moon supports science in several disciplines outside of planetary science. Moon to Mars Objectives have also been defined for Biological and Physical Sciences, Heliophysics, and Astrophysics.

As discussed throughout this document, there are several actions being taken in the near term (~2 years) to acquire the information and data needed to continue to build and define this strategy. This Implementation Plan will be updated on a roughly biannual basis and will incorporate the results of these and other efforts as our capabilities evolve.

1 Introduction

In April 2022, the National Academies of Science, Engineering, and Medicine delivered Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032 (OWL). This community-driven consensus document provides an important summary of the current state of the field and strategic guidance for the next 10 years of planetary science research and exploration. This decadal survey encompassed the full scope of planetary science, including subfields such as astrobiology, planetary defense, and science for human exploration, as well as the state of the profession. In addition, rather than being structured around the exploration of specific targets, this report was centered around 12 cross-cutting priority science questions under three themes: Origins; Worlds and Processes; and Life and Habitability.

Despite the wide-ranging focus of the three themes and 12 questions, lunar science and exploration is relevant throughout—demonstrating that the Moon is a vital cornerstone of planetary science and exploration. Studies or exploration of the Moon are relevant to all three themes, strongly relevant to six of the priority questions, and somewhat relevant to another four of them. In fact, the Decadal Survey defines three overarching "Science Themes for Lunar Exploration" (OWL Box 22.2):

Science Theme 1: Uncover the lunar record of solar system origin and early history. The Moon's composition, structure, and ancient surface preserve a record of early events: from the giant impact that produced the Earth−Moon system to ongoing bombardment as life on Earth emerged and evolved.

Science Theme 2: Understand the geologic processes that shaped the early Earth that are best preserved on the Moon. The Moon retains a record of processes that set the evolutionary paths of rocky worlds, including volcanism, magnetism, tectonism, and impacts.

Science Theme 3: Reveal inner solar system volatile origin and delivery processes. The Moon hosts water and other volatiles in its interior, across its surface, and in ice deposits at its poles, providing a record that may help constrain the origins of Earth's oceans and the building blocks for life, as well as ongoing volatile-delivery processes.

Further, the Decadal Survey made several recommendations about lunar science and exploration, including **Recommendation 19-3: [NASA] should develop a strategic lunar program that includes human exploration as an additional option to robotic missions to achieve decadal-level science goals at the Moon.**

In parallel with the Decadal Survey release, NASA delivered the first iteration of its Moon to Mars (M2M) Objectives in September 2022, with an update (NASA's Moon to Mars Strategy and Objectives Development) in April 2023, which establishes and documents an objectives-based approach to NASA's human deep-space exploration efforts. The M2M Strategy is dynamic; it will be iterated and updated annually with input and feedback from all the stakeholders, including the science community. The M2M objectives were developed to guide NASA's exploration strategy through the return of astronauts to the Moon, through sustained lunar science and exploration, and through to crewed landings on Mars, along with the associated science and technology developments required along the way to achieve science objectives. The M2M framework contains 63 top-level objectives and corresponding goals, along with the rationale behind each goal, and nine recurring tenets that capture common themes that are broadly applicable across the objectives. The goals cover the broad areas of science, transportation and habitation, lunar and Martian infrastructure, and operations and can be found in the document linked above. Among the 63 goals are 13 science objectives, including 4 each for planetary science and heliophysics, 2 for physical sciences (including astrophysics), and 3 for human and biological sciences.

Of the four planetary science goals in the M2M Strategy, three are relevant to both the Moon and Mars (the fourth is only relevant to Mars). The lunar-relevant objectives draw directly from the Decadal Survey's "Science Themes for Lunar Exploration" discussed above, and were created and iterated with feedback from community members:

LPS-1: Uncover the record of solar system origin and early history, by determining how and when planetary bodies formed and differentiated, characterizing the impact chronology of the inner solar system as recorded on the Moon and Mars, and characterize how impact rates in the inner solar system have changed over time as recorded on the Moon and Mars.

LPS-2: Advance understanding of the geologic processes affecting planetary bodies by determining interior structures, characterizing magmatic histories, characterizing ancient, modern, and evolution of atmospheres/ exospheres, and investigating how active processes modify the surfaces of the Moon and Mars.

LPS-3: Reveal inner solar system volatile origin and delivery processes by determining the age, origin, distribution, abundance, composition, transport, and sequestration of lunar and Martian volatiles.

This Implementation Plan provides a snapshot of NASA's continuing efforts to develop the strategy recommended in OWL and to address the M2M objectives relevant to lunar science. It is an opportunity to:

- present the full scope of tools currently available to NASA and how they map to high-priority lunar science that can be accomplished at the Moon; and
- build a plan for future NASA-led, lunar-focused science and exploration activities that is flexible and can be adapted to a changing landscape (i.e., capability growth, priority evolution, and budgetary fluctuation).

In addition to lunar science, lunar exploration and missions to the Moon present opportunities to meet the objectives and address priorities of NASA Science Mission Directorate (SMD) Divisions outside of the Planetary Science Division, (i.e., Astrophysics, Heliophysics, and Biological and Physical Sciences Divisions). However, lunar and planetary science objectives remain the focus of this Implementation Plan. A brief outline of the other Division's M2M science objectives and activities is provided in Section 6.

This document is focused on the science we can extract from the current and evolving lunar architecture and does not discuss the important role that science plays in enabling exploration. The science community's input is critical for supporting lunar exploration through defining landing sites and traverses, understanding soil properties, evaluating ISRU potential, and more, but that is not the purpose of this particular document.

Like the M2M Strategy, the Implementation Plan presented here is dynamic; it will continue to evolve as available capabilities and priorities evolve. Over the next several years NASA will conduct mission studies, assemble Science Definition Teams (SDTs), commission National Academies studies, hold workshops, and request Specific Action Teams (SATs) from the Planetary Science Assessment/Analysis Groups (AGs). In this way, community-driven inputs will be obtained to help make informed decisions about the strategies for addressing the six 'big challenges' defined below and the direction for lunar exploration overall. It is anticipated that this Implementation Plan will be updated on a roughly biannual basis, with opportunities for community comment on each iteration.

This Implementation Plan begins with a discussion of the six biggest lunar science challenges. Potential mission options for meeting these challenges are presented, along with a discussion of how they may be implemented. It also provides a strategic path forward for a range of mission-supporting infrastructures and activities, before ending with a summary of the top priorities for NASA's lunar science and exploration activities, and a discussion of immediate next steps.

2 Lunar Science: The Six Big Challenges

Based on an assessment of the OWL and M2M objectives, as well as previous guidance from the Scientific Context for the Exploration of the Moon (SCEM) and Advancing Science of the Moon (ASM) reports, the six biggest lunar science challenges, i.e., those whose implementation requires a strategy in order to achieve, have been identified. This list is not intended to be comprehensive; comprehensive lists of objectives can be found in those previously mentioned and other documents. Rather, the purpose of this document is to focus on developing strategies that enable these most difficult challenges while maintaining the infrastructure that allows progress on all of our objectives. Three of these challenges are lunar-surface-mission focused, with specific aims that can potentially be achieved through various architecture options. In priority order, they are:

- South Pole-Aitken (SPA) Basin Sample Return
- Lunar Geophysical Network
- Cryogenic Volatile Sample Return

To ensure these three challenges are met, NASA will need considered and deliberate plans.

The other three challenges require a buildup of knowledge and global access to lunar samples and other lunar data to meet. The objectives of these challenges cannot be achieved with any single mission, instead a strategy will be necessary to ensure that these objectives are part of the planning for all lunar science and exploration activities. Because they are not tied to a specific mission and need to be considered with all activities, they are not prioritized. They are:

- Lunar Chronology
- Lunar Formation and Evolution
- Lunar Volatiles

Each of these six big challenges can be traced to high priorities in both the OWL and M2M objectives (Table 1).

Table 1. The six big challenges mapped to OWL and M2M objectives.

	OWL Objectives	**M2M Objectives**
SPA Sample Return	Q3, Q4, Q5	LPS-1, LPS-2
Lunar Geophysical Network	Q5, Q8	LPS-2
Cryogenic Volatile Sample Return	Q3, Q4, Q5, Q10?	LPS-3
Lunar Chronology	Q4	LPS-1, LPS-2
Lunar Formation and Evolution	Q3, Q4, Q5	LPS-1, LPS-2
Lunar Volatiles	Q5, Q6	LPS-3

2.1 South Pole-Aitken (SPA) Basin Sample Return

South Pole-Aitken basin (SPA) sample return is one of the highest priority lunar science objectives in all planetary science Decadal Surveys, for several reasons. First and foremost, the SPA basin is the deepest, largest impact basin on the Moon, and likely the oldest. Rocks within SPA therefore hold the key to understanding the early evolution of the Moon, Earth, and solar system. The scientific yield of SPA sample analyses is likely to be paradigm shifting. For example:

- Samples from SPA will provide crucial tests to the late-heavy bombardment, or cataclysm, hypothesis as well as the leading paradigm of planetary differentiation or magma ocean hypothesis, if the SPA-forming impact excavated materials from the Moon's mantle.
- Determining the age of SPA (from radiometric age dating of samples) will:
    - help place constraints on the ages of other lunar impact basins and on episodes of ancient volcanic activity; and
    - provide additional information on the thermal state of the Moon during the time of impact (SPA samples can be used to investigate sources and distribution of heat-producing elements, and to thus understand the Moon's differentiation and thermal evolution).
- SPA samples will reveal the rock types and compositions of impact melt produced by the impact-forming event, and clasts within the samples may reveal the original target lithologies, e.g., deep-crustal and/or mantle components.
- SPA basin is perceived to contain substantial mafic minerals, as evidenced by remote sensing data, which are thought to be directly sourced from the lunar mantle. Such samples would allow, for the first time, direct analyses of lunar mantle materials and critical tests of the magma ocean hypothesis that has dominated early lunar evolutionary modeling since the 1970s. SPA sample analyses will also provide crucial ground truth for remote sensing datasets that suggest the presence of lower crustal and/or mantle materials within the basin.

Since the formation of SPA, more than 4 billion years of subsequent impacts have occurred within the basin—making SPA sample selection and analyses particularly challenging. It is imperative that SPA samples be returned for analysis on Earth, rather than be studied through in-situ analyses, so that the highest-precision dating and other state-of-the-art analytical methods can be used to comprehensively understand the complexity of the SPA samples. Similarly, the challenges of sample selection, requiring the return of the most relevant samples, will necessitate a rich complement of science instrumentation on-board lunar rovers and in the hands of astronauts.

2.2 Lunar Geophysical Network

Although scientifically important in situ geophysical data were obtained with the Apollo Lunar Surface Experiments Packages (ALSEPs) and Lunokhod retroreflectors in the 1960s and 1970s, these data have several limitations and substantial questions relating to nature and evolution of the lunar interior remain. It has therefore long been an aim of the lunar science community to deploy a long-lived, globally distributed network of geophysical instruments on the lunar surface—referred to as the Lunar Geophysical Network (LGN).

The geophysical measurements obtained with LGN would include seismic, heat flow, laser ranging, and magnetic field/electromagnetic sounding. To provide significant improvements in the science return of the LGN, compared with the Apollo-era data, it has been shown (ILN SDT Report, Cohen et al, 2009) that a minimum of four globally distributed stations would be required. For example, this would allow seismic event location and timing to be reliably derived and thus provide useful insights into the radial structure of the lunar interior and the present-day thermal gradient (selenotherm).

Understanding the occurrence and distribution of present-day seismic activity would shed light on both the lunar interior and on ongoing tectonic activity on the Moon. It is thought that at least some of the shallow moonquakes observed in the Apollo seismic catalog are related to tectonic activity related to global contraction and fault slip on lobate scarps. Global contraction of the Moon (and other terrestrial bodies) is linked to the global thermal history of these bodies and would provide important insight into the thermal evolution of the Moon.

As described in the OWL (Chapter 22), the three objectives for LGN are:

- Determine the internal structure and size of the crust, mantle, and core to constrain the composition, mineralogy, and lithologic variability of the Moon.
- Determine the distribution and origin of lunar seismic activity in order to better understand the origin of moonquakes and provide insights into the current dynamics of the lunar interior and the interplay with the external phenomena such as tidal interactions with Earth.
- Determine the global heat-flow budget for the Moon in order to more precisely constrain the distribution of heat-producing elements in the crust and mantle, the origin and nature of the Moon's asymmetry, its thermal evolution, and the extent it was initially melted.

In addition to characterizing the physical properties of the lunar interior, an LGN could also be used to help constrain the current electrostatic charging environment and the current impact flux at the lunar surface, both of which are important for surface exploration.

2.3 Cryogenic Volatile Sample Return

OWL emphasizes the importance of obtaining ices found within permanently shadowed regions at the lunar poles and returning them in their pristine cryogenic state for study in terrestrial labs. Determining the amount and origin of water ice on the Moon, measuring H and O isotopes, and understanding the nature and abundance of other constituents within the ice will help determine the origin of the volatiles and improve our understanding of the sources and sinks of water at the Moon and throughout the inner solar system.

Beyond the Moon, the technology that will be developed for collecting, transporting, curating and analyzing lunar cryogenic samples will have implications for driving technology developments toward cryogenic sample return from other planetary bodies, e.g., Mercury, Mars, comets, asteroids, and ocean worlds.

2.4 Lunar Chronology

The lunar surface provides a well-preserved record of the bombardment history of the inner solar system. Multiple community documents, including OWL, have prioritized constraining the chronology of key lunar terrains to enhance understanding of the geologic history of the Moon itself, as well as other solar system bodies. Some of the major planetary science goals relating to lunar chronology, indeed some of the highest-priority science from the Decadal Survey, include:

- Test the cataclysm hypothesis by examining the ages of lunar basins. This issue has substantial implications for planetary bodies throughout the inner solar system, including the early Earth. Many studies recommend anchoring the early Earth-Moon impact-flux curve by determining the age of the oldest lunar basin (South Pole-Aitken basin [see Section 2.1]) as part of this goal.
- Establish a precise absolute chronology across planetary surfaces; lunar chronology is used as a baseline underpinning the modeling of ages on Mars, Mercury, and other cratered bodies. Samples need to be collected from benchmark impact basins and craters that are distributed geographically around the Moon and that are temporally representative of the collisional evolution of the Moon.
- Determine the longevity of the lunar ‘heat engine.’ Obtaining absolute ages by analyzing samples of the youngest mare basalts would help constrain the longevity of the lunar heat engine and provide the most modern tie point for the lunar crater-flux curve.

A relatively large suite of samples, from several representative locations for which extensive contextual information is available, needs to be collected and analyzed to achieve these science goals. This is particularly challenging because the samples need to be carefully selected and obtained from multiple locations across the lunar globe.

2.5 Lunar Formation and Evolution

Some of the highest-level questions posed in OWL relate to the earliest formation and geologic history of the Moon. As the Decadal Survey highlights (OWL, Chapter 2), there are major ongoing debates over multiple topics, including:

- Models of the giant impact Moon-forming event
- Formation age of the Moon
- Lunar formation and evolution processes, as determined from the inventory of endogenic volatiles
- The asymmetry of the Moon
- The Moon's ancient magnetic field
- The possibility of recent volcanism (e.g., within the past 1 billion years) on the Moon

To make substantial inroads into these topics, a wide variety of geophysical and geochemical analyses, from a range of platforms and implementation methods, will be required (e.g., see OWL, Chapter 6), including:

- Geophysical measurements from orbit and/or a seismic network and other in situ analyses
- Geophysical measurements from surface instrumentation (globally distributed seismic and heat flow network, as well as remanent magnetization, resistivity, and ground-penetrating radar measurements)
- Geochemical, mineralogical, isotopic (including radiometric dating), and paleomagnetic measurements of a diverse set of lunar samples (from returned samples, in-situ measurements, and orbital platforms) and regions. In particular, measurements from the South Pole-Aitken basin would provide important information about the lunar interior by obtaining samples from the lower crust/upper mantle

These measurements and analyses must also be coupled with continued laboratory experimentation and modeling studies. Indeed, the sheer number of inputs to this big challenge makes addressing the science goals extremely complex.

2.6 Lunar Volatiles

The Moon has water and other volatiles in its interior, across its surface, and in ice deposits at the poles. The complex interactions of volatiles between the space environment and the regolith including production, transport, and sequestration, are fundamental to airless bodies, and the Moon is an excellent laboratory in which to study these processes. Further, lunar PSR deposits may preserve the volatile history of the Earth–Moon system, including the delivery of organics to Earth.

Orbital and in situ measurements, as well as sealed and conditioned (cold) samples will allow scientists to make progress towards several OWL objectives:

- Determine the origin, time of delivery, vertical and lateral distribution, and current cycling of cold-trapped lunar volatiles via in situ analyses of isotopes (e.g., deuterium/hydrogen), sulfur, organics, abundance and distribution of volatiles, and local exospheric measurements. (Q5.5)
- Determine the range of volatile contents and species in planetary melts in igneous samples from Mars, the Moon, and asteroids, to constrain the range and variety in planetary volatile contents, and factors influencing melt generation, composition, and eruptibility using Earth-based laboratory measurements of returned samples and/or meteorites. (Q5.3)
- Derive the sources of exospheric volatiles by measuring the distribution, composition, and abundance of surface volatiles (including in permanently shadowed regions) on solid bodies including the Moon, Mercury, Ceres, and outer planet satellites such as Europa. (Q6.1)
- Relate the loss of volatiles from surface boundary exospheres to solar wind dynamics and quantify the effects of magnetic fields by measuring escaping, migrating, and bound species in regions of different magnetic topology (e.g., Mercury and Ganymede polar and equatorial regions and lunar magnetic anomalies). (Q6.5)

3 Strategic Plans for Lunar Missions

3.1 Competed Missions

Competed missions are an important part of NASA's strategy for realizing its science objectives, including its lunar science objectives. NASA has three programs for competed planetary science missions: New Frontiers, Discovery, and Small Innovative Missions for Planetary Exploration (SIMPLEx), with approximate full-mission costs of up to $2B, $1B, and $100M, respectively. For all these programs, mission proposals are solicited from the community to meet NASA objectives and priorities. As of 2024, there are no firm dates for any Announcements of Opportunity for these three programs.

The SIMPLEx and Discovery programs are open to all planetary science destinations and science objectives, including lunar science. Two lunar-focused SIMPLEx missions have previously been selected (Lunar Polar Hydrogen Mapper and Lunar Trailblazer), and two lunar-focused Discovery missions have previously been completed (Lunar Prospector and Gravity Recovery and Interior Laboratory (GRAIL).

In contrast, for New Frontiers there is a list of solicited targets and science objectives, based on input from National Academies reports and Decadal Surveys. The most recent New Frontiers solicitation (NF4) included a Lunar South Pole-Aitken Basin Sample Return mission. Both a Lunar South Pole-Aitken Basin Sample Return mission and a Lunar Geophysical Network mission were included in the draft NF5 solicitation, however, as of September 2023, NF5 has been delayed and a call is not expected to be released before 2026. The list of solicited targets will be reconsidered by the National Academies before that call is released.

In addition, Payloads and Research Investigations on the Surface of the Moon (PRISM) allows for competitively selected payload suites to be manifested on commercial (CLPS) landers (see section 3.3.1 below).

Any future lunar-relevant selections in the competed mission programs will be factored into future iterations of this document.

3.2 Directed Missions

A directed mission is initiated when NASA determines there is a strategic need for a mission that falls outside of the normal competitive process. NASA may decide that there are strategic needs for new lunar missions. The implementation of these missions may be openly competed, internally competed, or directed to a particular NASA Center. If the mission itself is not openly competed, it is NASA practice that most, or all, of the science instruments and science teams for such missions are openly competed.

In the near term, the Lunar Reconnaissance Orbiter (LRO) is a directed mission designed to meet NASA's human exploration and science needs. LRO returns high-resolution imagery and other science datasets to address lunar science objectives and to aid in preparation for human exploration of the Moon.

From 2019 through 2024, SMD was pursuing the Volatiles Investigating Polar Exploration Rover (VIPER) as a path to provide volatile data at the south polar region. As of July 17, 2024, NASA has terminated the VIPER mission due to lander delays, future budget risks, and overall Science Mission Directorate funding constraints. NASA has notified Congress of the agency's intent. NASA is investigating external partnerships with domestic and international entities who may be interested in completing the VIPER rover and conducting the VIPER mission on the lunar surface that maximize value to the Agency through innovative mission concepts and arrangements.

As we look to make strategic decisions about future investments, two additional potential lunar-focused directed missions are currently being investigated through ongoing studies: Endurance-A and Lunar Exploration and Science Orbiter (LExSO). Future studies are also planned to understand the scope and viability of a potential Lunar Geophysical Network deployed by NASA's Commercial Lunar Payload Services (see Section 3.3).

3.2.1 Endurance

The Endurance-A (referred to as "Endurance" hereafter) mission concept was proposed in OWL as a potential architecture for achieving sample return from the SPA basin. In this concept, a long-duration rover would traverse across SPA and cache samples from strategic sites; the samples would be delivered to Artemis astronauts and then brought to Earth (the "A" stands for "Astronauts"; a second concept that utilized purely robotic sample return was also studied and given the name Endurance-R). A study of the Endurance concept by the Jet Propulsion Laboratory (JPL) is underway in 2024, and a science definition team is being stood up (from members of the science community) to better define (i.e., explore the architectural trade space) the science objectives and requirements for Endurance.

Science goals for an SPA sample return and exploration mission as proposed by OWL include determining:

- The age of SPA, the largest and oldest impact basin on the Moon, to anchor the earliest impact history of the solar system.
- Testing the giant planet migration and terminal cataclysm hypotheses, to better constrain the inner solar system impact chronology used to date the surfaces of other planetary bodies.
- The age and mineralogical and geochemical composition of deep and crustal materials exposed in SPA to understand the bulk composition of the Moon, its primordial differentiation and geologic evolution, and the significance of chronologic measurements completed on nearside samples for timing lunar solidification.

- The age and nature of volcanic features and compositional anomalies on the lunar farside to characterize the thermochemical evolution of terrestrial worlds and constrain the origin of the Moon's nearside-farside asymmetry.
- The geologic diversity of the SPA Terrane to provide geologic context for returned samples, ground truth for orbital measurements, and characterize the surface processes that shape planetary bodies.

The SDT will refine and prioritize science goals for an SPA mission. A South Pole-Aitken Basin sample return and exploration mission would provide crucial information regarding the early history of the solar system by determining the age of the SPA basin and characterizing how impact rates in the inner solar system have changed over time (LPS-1). Such a mission would also advance our understanding of geologic processes that have affected the lunar surface (LPS-2).

Implementation approaches will be addressed by the SDT in conjunction with a JPL technical team, with a final implementation approach chosen by NASA upon completion of the SDT and evaluation of the final SDT report. The payloads for an SPA sample return and exploration mission will be competed at a later date.

3.2.2 LExSO

Although efforts are being made to extend LRO's life as long as possible, it is already more than a decade past its planned lifetime and will not last forever; we are likely to lose this important asset just as the new era of lunar exploration begins in earnest. It is therefore prudent to consider the necessary capabilities of a follow-on, robust, orbital mission that would meet the needs of both the science and exploration communities during the era of crewed Artemis surface missions. Orbital measurements from next generation instruments can help address many high priority science objectives related to lunar volatiles and constrain objectives related to lunar chronology and lunar formation. In 2023, a pre-phase-A study was conducted by the Goddard Space Flight Center (GSFC) to help define a follow-on mission based on science goals, as defined in the LEAG Continuous Lunar Orbital Capabilities Specific Action Team report, and human exploration needs, as defined by the requirements of the M2M architecture and in consultation with stakeholders in the Exploration Systems Development Mission Directorate (ESDMD).

The mission concept developed in that study, known as LExSO (Lunar Exploration and Science Orbiter), would have polar mapping capabilities and utilize frozen elliptical orbits, similar to the orbit LRO has now used for much of its orbital life. The study also considered the ability for a circular mapping orbit, providing access to the entire lunar surface for portions of the mission, to enable higher-data resolution over non-south polar targets and an option for optical communication with high-bandwidth data flow.

LExSO would address a mix of science and exploration goals:

- Establish connections between orbital observations with exploration sites of surface volatiles
- Determine how anthropogenic volatiles distribute and accumulate in the lunar environment, and infer regolith adsorption properties

- Characterize present-day and recent impact processes and their products
- Determine how illumination, solar wind, and micrometeoroid bombardment affect the lunar water cycle globally and within local extreme polar environments
- Characterize recent and modern mass-wasting and tectonic activity
- Determine the emplacement history and nature of geologically recent volcanic activity and products
- Characterize the structure and physical properties of the regolith
- Determine the distribution and concentration of polar volatiles (specifically OH and H2O)
- Evaluate the terrain and topography of the lunar surface at lander scales to minimize hazard avoidance planning for human and robotic missions
- Support traverse planning and science targeting for Artemis and robotic mission surface operations
- Document the effects of human and robotic exploration on the natural environment
- Provide support for urgent surface location services

A design reference suite of instruments has been presented to the community at several venues and feedback from the science, exploration, and commercial communities was incorporated into the study.

The mission has not yet been approved for future funding and a procurement strategy has not yet been defined, but implementation options would include either competing the entire mission or directing the mission and competing the instruments and science team. Based on priorities outlined in the OWL, a future lunar orbiter, however, is currently deemed to be lower budget priority than the “big challenge” missions (i.e., SPA basin sample return, Lunar Geophysical Network, and Cryogenic Sample Return).

3.3 Commercial Lunar Payload Services

NASA’s Commercial Lunar Payload Services (CLPS) initiative is an innovative, service-based, competitive acquisition model that enables rapid, affordable, and frequent access to the lunar surface via a growing market of American commercial providers. CLPS payloads are customer-owned delivered items and the missions themselves are owned by the service providers rather than NASA. With CLPS, NASA aims to grow the lunar economy by increasing the number of commercial entities that can land on the Moon, expand commercial service activities to include a range of new capabilities, and affordably conduct high-priority science investigations. NASA aims to be one of many customers for CLPS services.

CLPS deliveries are initiated using Task Orders (TOs) and, as of 2024, 14 companies are eligible to bid in response to these task orders to carry NASA payloads to the lunar surface. These TOs list the payloads to be delivered to the surface and provide constraints on specific needs of the manifested instruments, as well as outline the anticipated landing site for the delivery. NASA currently maintains a cadence of approximately two new TOs per year. Although the TOs are primarily sponsored by SMD, payloads from other mission directorates and international agencies are often included.

As of 2024, ten contracted deliveries with more than 50 NASA instruments have been awarded to five commercial companies, and destinations for three subsequent task orders have been identified, with contracts for these not yet awarded (Table 2). More information about each of these deliveries and the payloads they are carrying can be found on the CLPS section of the ESSIO website.

Table 2: List of CLPS Task Orders to-date

Task Order[a]	**Landing Site**	**NASA Payloads**[c]	**Awarded Vendor**
TO2-AB	Sinus Viscositatis	NPLP	Astrobotic
TO2-IM	South Polar Site	NPLP	Intuitive Machines
TO-19C[b]	Haworth Crater	LSITP	Masten[b]
TO PRIME-1	Shackleton Connecting Ridge	ISRU Demo	Intuitive Machines
TO-20A	Mons Mouton	VIPER Mass Model	Astrobotic
TO-19D	Crisium Basin	LSITP	Firefly Aerospace
CP-11	Reiner Gamma	PRISM-1/Int'l	Intuitive Machines
CP-12	Schrödinger Basin	PRISM-1	Draper
CP-21	Gruithuisen Domes	PRISM-2/LSITP	TBD
CP-22	South Polar Region	PRISM-2	Intuitive Machines
CS-3 & CS-4	Lunar Far Side & Orbital Insertion	Calibration Source DOE	Firefly Aerospace
CP-31	INA (Irregular Mare Patch)	PRISM-3	TBD
CT-3	South Polar Region		Blue Origin
CS-6	South Polar Region		TBD

[a] TO = Task Order; CP = CLPS PRISM delivery; CS = CLPS Science delivery.

[b] At the time of writing, Masten has filed for Chapter 11 bankruptcy and its assets have been acquired by Astrobotic. NASA is currently evaluating ways to remanifest the remaining TO-19C payloads on future CLPS deliveries.

[c] This column notes the mechanism(s) by which payloads for the delivery were solicited or obtained. Some solicitations had multiple selections. NPLP = NASA-Provided Lunar Payloads; LSITP = Lunar Surface Instrument and Technology Payloads; PRISM = Payloads and Research Investigations on the Surface of the Moon; DoE = Department of Energy.

3.3.1 CLPS Payloads

NASA payloads selected for CLPS delivery will produce new and complementary datasets to help answer high-priority science questions, demonstrate new technologies and capabilities, and prepare the way for human surface exploration.

The payloads for the first CLPS deliveries were solicited from the NASA-Provided Lunar Payloads (NPLP; NASA-internal) and Lunar Surface Instrument and Technology Payloads (LSITP; external to NASA) programs. Both these programs were focused on obtaining individual payloads that could be available rapidly, such as existing flight spares or engineering models.

NASA now solicits science payloads for CLPS through the Payloads and Research Investigations on the Surface of the Moon (PRISM) program. PRISM supports investigations that include development (allowing more development time than LSITP/NPLP) and flight of science-driven suites of instruments to pre-defined or proposer-selected landing sites. These landing sites are high-science-value targets where unresolved lunar science questions can be addressed using CLPS platforms. PRISM proposals are solicited roughly annually through NASA's Research Opportunities in Space and Earth Sciences (ROSES) research announcement, and PRISM is the primary mechanism for manifesting NASA CLPS payloads.

3.3.2 Future of CLPS

CLPS will continue to support lunar science and exploration in a variety of ways. For example:

- CLPS may support Artemis crewed activities through delivery of scientific equipment, supplies for longer duration missions, and human-centric infrastructure (e.g., the lunar terrain vehicle, ISRU demonstrations, equipment).
- CLPS may evolve to develop capabilities necessary for enabling enhanced science investigations on the Moon. Such capabilities could include, but are not limited to:
  - mobility over several kilometers;
  - operation in low-temperature environments;
  - surviving and operating through the lunar night (both for short-term and multi-year campaigns);
  - sample manipulation (e.g., with robotic arms); and
  - sample return.

Neither NASA nor CLPS vendors can currently afford to develop all these desired capabilities simultaneously. Strategic planning and investments are therefore required to maximize science opportunities, prioritize capabilities, and support the establishment of a sustainable lunar economy. To that end, NASA regularly surveys the CLPS vendor pool to determine their current and near-term future capabilities. In addition, selected PRISM payloads provide a sense of the cost of adding new capabilities to CLPS deliveries which allows for better future planning and increases understanding of the kind of high-priority science that can be conducted within the PRISM cost cap.

A long-term strategy for the future of the CLPS program and PRISM solicitations, including acquisition strategies and science goal planning, is part of our 2-year plan for strategy development, as we learn more about CLPS success rates and capabilities.

3.4 Artemis

Artemis will return human explorers to the surface of the Moon for the first time since Apollo. Science is one of the pillars of Artemis and NASA is working to maximize the science that can be accomplished through human exploration. After the successful uncrewed Artemis 1 mission in November 2022, NASA is working toward the Artemis II mission, targeted for September 2025, which will take four astronauts to cis-lunar space and back. Artemis III will be the first surface mission and is currently scheduled for September 2026. While early sorties will have limited capability, those capabilities will grow and expand as Artemis builds towards longer duration stays and a sustainable human presence. Artemis is targeting the lunar south polar region for initial exploration, but ultimately will have the capabilities for global access.

The overarching science objectives for Artemis are captured by the Moon to Mars Lunar and Planetary Science Objectives 1-3:

- LPS-1: : Uncover the record of solar system origin and early history.
- LPS-2: Advance understanding of the geologic processes affecting planetary bodies.
- LPS-3: Reveal inner solar system volatile origin and delivery processes.

Specific goals for Artemis III and other short duration polar sorties are outlined in the Artemis III Science Definition Team report and will be further developed and refined by the selected teams for each mission. Two separate National Academy studies are planned to develop lunar science objectives for Artemis, one focused on the science that can be accomplished by human explorers on non-polar sorties and one focused on the science that can be accomplished during the sustained phase of Artemis with repeat visits and longer duration stays.

4 Paths Forward for the Big Challenges

Table 3 illustrates the current potential mission architectures (as described in Section 3) that are currently being considered to address the six big challenges for lunar science (Section 2). These options are discussed in further detail in the following sections.

Table 3. Mission architecture options under consideration for meeting the six lunar science 'big challenges'.

		Big Challenge					
		SPA Sample Return	**LGN**	**Cryogenic Sample Return**	**Chronology**	**Formation & Evolution**	**Volatiles**
Potential Architecture	**Competed Mission**	New Frontiers	New Frontiers		Discovery, SIMPLEX	Discovery, SIMPLEX	Lunar Trailblazer, Discovery, SIMPLEX
	Strategic Mission	Endurance		Artemis	Endurance	Endurance	LExSO
	CLPS	Additional capabilities required	With Current/ Future Capabilities	Additional Capabilities Required	With Current/ Future Capabilities	With Current/ Future Capabilities	With Current/ Future Capabilities
	Artemis Human Sorties	Polar/Non-Polar Sorties	Polar/Non-Polar Sorties	Polar Sorties	Polar/Non-Polar Sorties	Polar/Non-Polar Sorties	Polar/Non-Polar Sorties

4.1 South Pole–Aitken Basin Sample Return

As illustrated in Table 3, there are several potential approaches that can be used to address SPA basin science objectives—all of which need to achieve sample return from well-defined locations in SPA. One potential approach, suggested in OWL, is the Endurance concept (see Section 3.2.1). Robotic sample return without astronaut involvement is another potential approach and is the reason this objective has been previously on the New Frontiers list. However, it would be difficult to achieve all the science goals unless mobility is available for roving to collect the required samples. An additional option for bringing SPA samples to Earth could be presented by CLPS, if capabilities increase sufficiently to include sample return. Finally, one or more human sorties to the interior of SPA is another possible option for sample collection, but mission limitations mean it may not be possible to visit all the scientifically important locations in SPA.

Several paths are currently being pursued before a decision on how to best achieve SPA Sample Return is made:

- JPL is currently conducting a study to further define the rover requirements and potential payloads of the Endurance concept (see Section 3.2.1).
- Additional mission studies are being considered to look at different approaches for a long-duration sample-collecting rover (e.g., a rover developed for science, or a Lunar Terrain Vehicle (LTV)-derived rover).
- Mobility as a CLPS service is another avenue that is being explored by NASA as a lower-cost solution for roving capabilities in SPA, as well as the potential for CLPS capabilities to evolve to include sample return.
- A Science Definition Team study is being initiated to build upon the OWL recommendations and JPL studies to outline science objectives and their measurement requirements and what architecture options may be best suited for meeting those science objectives.
- A National Academies study on non-polar human sorties has been initiated, the results of which may also provide important information on the viability of using human sorties to conduct SPA Sample Return.

4.2 Lunar Geophysical Network

LGN was formerly on the New Frontiers Mission Concepts list for NF5, but as discussed above in Section 3.1, NASA will be asking for input from the National Academies to determine the list for NF5 when that solicitation moves forward, so its future viability through NF is uncertain at this time. Multiple CLPS deliveries of long-duration landers or self-contained long-duration payloads may be a viable route to deliver the required components of an LGN (see Section 2.2). In addition, both polar and non-polar human sorties through Artemis would provide an opportunity for delivery of LGN nodes or components. A benefit of a multi-year network is that, once established, it can be built upon and expanded, meaning a combination of robotic- and crew-deployed nodes can be utilized. International contributions may be incorporated as well.

Going forward, NASA plans to perform a payload design study to help understand the trades for deploying stand-alone LGN packages versus LGN payloads that are integrated onto a lander. This study will thus help define if or how CLPS might be utilized for LGN purposes and if an entire lander needs to survive long-term, or just the payloads.

4.3 Cryogenic Volatile Sample Return

The first step of cryogenic volatile sample return is to fully understand the science drivers and science community's needs for these samples. To that end, a joint Lunar Exploration Analysis Group (LEAG) and Extraterrestrial Materials Assessment Group (ExMAG) Specific Action Team (SAT) was established to address those and other questions about Artemis samples (including cryogenic samples). This consists of three panels focusing on Volatile Samples, Nominal Samples, and Sample Data Infrastructure.

The value of human manipulation of the complex sampling tools that will be required for the collection and return of samples at cryogenic temperatures is clear and it is therefore assumed that cryogenic sample collection will be achieved via crewed Artemis missions. The difficulty of collecting, transporting, curating, and analyzing pristine cryogenic samples, however, should not be underestimated. Developing the capability for cold and cryogenic sample return is an important goal of the Artemis architecture.

An internal study was recently completed by ESDMD to understand the current state of knowledge on this topic and define a path forward, which identified specific challenges related to cryogenic sample extraction and collection, including:

(i) Understanding how crew, tools, drills, etc., will perform in permanently shadowed environments; the early Artemis missions will better quantify these environments and the associated risks;
(ii) Preserving cryogenic sample integrity through drilling; this risk is being addressed in industry where the drilling technology for extraction of cryogenic samples is being developed; and
(iii) Operational constraints, e.g., extravehicular activity (EVA) time limits, communication delays, navigation challenges (up to three EVAs may be required to extract one 3-m/3.5-kg core sample); in-depth thermal analyses and technology developments for communication and navigation.

Transportation of cryogenic samples also presents a set of challenges. Freezers generally work in pressurized environments (i.e., requiring an atmosphere) and cooling in vacuum thus presents unique challenges; further technology developments are needed in this area. The current work is focused on modifying the Polar freezer, which is installed on the ISS, to achieve an initial -85°C capability.

Information about current and future curation plans for cold and cryogenic samples are provided in the discussion of Artemis Curation (Section 5.2).

In general, the scientific community is not ready to receive and analyze cold-curated samples, but the development of techniques for working with cold and cryogenic samples is solicited through NASA's Laboratory Analysis of Returned Samples (LARS) research program (see Section 5.4.1).

4.4 Lunar Chronology

There are two main options for achieving the goals of this challenge: in-situ analyses and sample return with subsequent analyses on Earth. Significant strides can be made by using in-situ dating and context analyses (e.g., imaging, spectroscopy). To enable this path, investments in instrument development for in-situ age dating (with a variety of chronometers) in a range of geologic settings is required. Demonstration of these chronometers and technologies in the lunar environment may then be achieved via CLPS platforms, or as payloads on other NASA robotic or crewed (Artemis) missions. The recent PRISM selection of DIMPLE (Dating an Irregular Mare Patch with a Lunar Explorer) will be the first deployed payload designed for in-situ dating of a planetary surface.

The in-situ approach, or autonomous sample return, through CLPS or other platforms would work best for sites where there is clear geologic context and/or little geologic diversity. For sites with complex stratigraphic relationships and extensive geologic diversity, however, having crew present to make field geologic observations and strategic sample collections may substantially enable meeting the required science objectives. As noted above (Section 4.1), a National Academies study has been initiated to help identify destinations of key interest beyond the south polar region that would specifically benefit from the presence of a crew for sample collection and return.

4.5 Lunar Formation and Evolution

Most of the implementation options for this challenge have been described in relation to the other big challenges. Indeed, by making progress towards meeting the SPA basin Sample Return, LGN, and lunar chronology challenges, progress will simultaneously be made towards the goals of better understanding lunar formation and evolution.

As outlined above, where surface measurements are required, robotic missions/CLPS platforms may provide viable options. Human operation of instrumentation, however, can enable more-accurate, and/or targeted analyses—and more of them. Likewise, in-situ analyses on samples can provide important data, but by returning samples to Earth for study, state-of-the-art laboratories and instrumentation can be used to provide superior results. In the near term, the National Academies study on the science enabled by non-polar sorties will provide important input into identifying other critical locations for crewed sample-return missions that will maximize understanding of lunar formation and evolution.

For this big challenge, it is also important to have capable next-generation orbital assets; satellites which can provide data that enables scientific advances beyond the results achieved from Lunar Prospector, LRO, GRAIL, and other previous lunar orbiters.

4.6 Volatiles

Advances in orbital and laboratory instrumentation within the last twenty years have allowed the science community to identify and recognize the complexity of lunar volatiles. The study of lunar volatiles is a young and very active field of research, and there is a lot of progress to be made in both laboratory analysis and remote sensing from orbit. The termination of the VIPER mission is a significant delay to volatile science, and none of the currently planned missions will acquire all of the science data that was anticipated from VIPER; however, there are several planned and potential missions that will contribute to our understanding of volatiles. From orbit, Lunar Trailblazer will provide an opportunity to target near IR water bands, and volatiles should be an important consideration for the instrument suite onboard LExSO or any other future lunar orbiter. Sample return of sealed, and eventually cold conditioned and cryogenic samples are an important part of our plans for Artemis human missions. Through the current LEAG/ExMAG studies, we are soliciting for information to understand the community's needs to develop the tools to analyze these samples. In-situ measurements, including both robotic and human-enabled will also be critical for understanding the volatiles story and several upcoming CLPS landers are delivering volatile-relevant instruments.

5 Strategic Directions for Mission-Supporting Infrastructure

In addition to the mission implementation options for advancing lunar science and exploration, a range of other mission-supporting infrastructures are required and feed into this overarching lunar implementation plan, as described in the following sections.

5.1 Artemis Science

Chapter 19 of OWL (human exploration) noted that, “To adequately include science requirements in lunar human exploration plans, an Artemis Science Team is necessary to identify and advocate for the highest-priority science questions to be addressed for Artemis.” NASA is continuing to assemble that team.

For the initial phase of Artemis missions (i.e., based around short-term sorties), the science team for each mission will be made up of three components (as illustrated in Figure 1) and listed below, with oversight from a NASA-selected Project Scientist. This Project Scientist will adjudicate any issues between the sub-teams and be a voice for that mission’s science within the Artemis Program. The Project Scientists for Artemis III and Artemis IV, Dr. Noah Petro and Dr. Barbara Cohen, respectively, were announced in March 2023. A Deputy Project scientist will also be named for each mission and will assist the Project Scientist with these activities.

Artemis Internal Science Team (AIST): The AIST was officially stood up in 2022 and is a small group of NASA lunar scientists (see Table 4) that have been working to ensure that science is integrated into every aspect of Artemis as architectures and hardware are developed. As Artemis develops, this team will make sure the architecture and systems can support science. The AIST members are embedded in boards and working groups across the agency, reviewing documents, and providing rapid response to requests and queries from across the agency by those developing hardware and in support of Artemis. They also serve as the interface between NASA and the competed Artemis teams to maximize science return. They lead classroom, field, and ops training for crew as well as the operational training for the competed geology and payload teams. This team also provides Artemis-program-level strategic planning. As the competed teams come on board to focus on each mission, this team determines both the short- and long-term requirements, ensures mission-to-mission continuity and makes sure that the needs of the entire community can be met.

Geology Team: A geology team will be competitively selected for each sortie mission through a ROSES call. The selected team will participate in the definition of scientific objectives to be addressed by the individual mission, the design and execution of the surface campaign to satisfy those objectives, and the evaluation of the data returned by the mission, including preliminary examination of returned samples. The geology team will support real-time mission operations in the Science Evaluation Room (SER), the collection and assessment of scientific data and mission-relevant information. After the surface mission is completed, members of the team will lead the effort to produce Preliminary Geology Mission and Preliminary Geology Science Reports. Members of the team with relevant experience will participate in the preliminary examination of samples at the direction of the Astromaterials Acquisition and Curation Office at the Johnson Space Center. As of August 2023, the competitively selected Geology Team for Artemis III has been named.

A participating scientist program will be planned for each mission to expand the geology team and provide additional expertise. The call will be open to international participants on a no-exchange-of-funds basis.

Payload Team(s): Deployed instruments for Artemis missions will largely be selected through competitive ROSES calls. Foreign-led proposals and foreign team members will be allowed on a no-exchange-of-funds basis. Payloads may also be directed based on NASA's needs and priorities. Science team members for these instruments will be part of the overall Artemis science team (Figure 1) for each Artemis mission. As of March 2024, the competitively selected First Lunar Instruments for Artemis Astronaut Deployment have been selected.

Figure 1. Structure of the science team for Artemis sortie-style missions.

Project Scientist

Artemis Internal Science Team	Competitively Selected Geology Team (including Participating Scientists)	Competitively Selected Payload Team(s)

Table 4: List of roles in the Artemis Internal Science Team.

AIST Role	Member (as of September 2024)
Training and Strategic Integration Lead	Cindy Evans
Science Flight Operations Lead	Kelsey Young
EVA Hardware and Testing Integration Lead	Trevor Graff
Sample Integrity Lead	Barbara Cohen
Contamination Control Scientist	Andrew Needham
Artemis Curation Lead	Juliane Gross
Mission Planning and Science Implementation Lead	Samuel Lawrence
Spatial Planning and Data Lead	Noah Petro
Software Systems Lead	Matthew Miller
SMD Payload Integration Officer	Renee Weber
SMD Surface Mobility Lead	Ryan Ewing

5.2 Curation

The Astromaterials Acquisition and Curation Office (herein “curation team”), in the Astromaterials Research and Science Division at NASA’s Johnson Space Center (JSC), is responsible for the curation of NASA’s extraterrestrial samples, including those from the Moon. Preparations are now underway to curate additional lunar samples obtained during the Artemis (and potentially CLPS) missions.

Although the current curation facilities at JSC are well equipped to handle sample return as part of Artemis III and IV, there are significant questions that need to be answered and capabilities that need to be developed to maximize the scientific return from sample return missions beyond Artemis IV.

The overarching plan for the curation of additional lunar samples over the next decade is predicated on several assumptions including:

- Artemis III and IV will each return ~100 kg of non-volatile sample and containers, all of which can be curated at ambient conditions, although the ratio of mass to sample container is yet to be determined.
- Artemis V will return ~5+ kg of non-volatile samples, all of which can be curated at ambient conditions. The amount of sample returned is limited given the mass constraints of the freezer required to return cold samples.
- Artemis V will return ~6 kg volatile samples that will be returned at -85°C. The amount of sample returned is limited given the mass constraints of the freezer required to return cold samples.
- A sample catalog, which will include sufficient information about the samples to allow scientists to make intelligible sample requests, for each Artemis mission is to be released six months after the return of samples.
- Any CLPS missions in the next decade that will return lunar samples will do so at ambient temperature and not provide cold curation.

The curation team is actively working with Artemis and the sample science community to anticipate and solve anticipated obstacles associated with the curation of new lunar samples from Artemis (and CLPS), as described here.

5.2.1 Curation of Samples Returned at Ambient Conditions

The majority of lunar samples returned at ambient conditions will be curated in the existing Apollo facilities at JSC. We expect, however, that some of the samples returned at ambient conditions will have associated volatile components (e.g., H), and Apollo Next Generation Sample Analysis (ANGSA) results have shown that there is value in freezing samples even if they were not initially returned frozen. Efforts are underway to determine the appropriate percentage and temperature of samples returned at ambient conditions to be frozen for future studies and community input is being sought through the LEAG-ExMAG Samples SAT discussed above (Section 4.3).

Samples may also be returned at ambient conditions, but in sealed containers. In these cases, the intention is to perform gas extraction from these samples, similar to what was done on the ANGSA samples (i.e., 73001 CSVC), potentially utilizing the existing setup or developing a similar one, depending on the sealed containers used for Artemis. Storage of sealed containers will also be in the existing Apollo facilities.

Although the current plan is to curate samples returned at ambient conditions in the current Apollo facility, there may not be enough room to continue to add new samples by the time of Artemis V. The curation team is actively working to determine if space in the Apollo facility can be re-optimized to provide additional storage. A similar concern exists for the laboratory at White Sands, which acts as a secondary storage location for NASA's extraterrestrial materials. The curation team is also working to explore different ways to re-optimize space at this location to make additional room for storage of samples from future sample return missions.

5.2.2 Cold Curation and Processing

Potentially beginning as early as Artemis V, samples will be returned in a frozen state to more closely mimic the environment in which they were collected. These samples are intended to be stored in commercially available -80°C freezers. Although insufficient space is currently available for such freezers in the existing Apollo curation facilities, there will be sufficient space in the Building 31 Annex currently being constructed at JSC.

There are still numerous open questions regarding the storage and processing of cold and cryogenic samples. With the completion of the Annex, sample processing capabilities will be in place to process samples at -20°C (253 K). If there is a need to process samples at -80°C, however, this will require the use of cold robotics, the development of which is at least five years away. To determine the cold curation and sample processing needs, some outstanding questions need to be answered, including:

- What science questions can be answered only if materials remain cold?
- What portion, if any, of the Artemis samples that are returned at ambient conditions should be curated under cold conditions?
- What storage temperature [cryogenic temperatures (10–25 K), LN2 temperatures (77 K), commercially available freezer temperatures (~190 K), nominal cold curation temperatures (~250 K), or nominal curation temperatures (~300 K)] will maximize the science return of these cold samples?
- What materials will be considered compatible in these conditions?
- How do we process cold/cryogenic materials at cold/cryogenic conditions?
- Are there specific hazards or toxic volatiles that may be present in samples that remain cold? If so, what safety protocols need to be established for handling?
- If cold samples are returned as a mixture of both volatiles and regolith/rock, should these be immediately separated after return or be stored together until allocated?

As noted in Section 4.3, a LEAG-ExMAG SAT is being conducted to address some of these questions. Community input will be crucial as future curation facilities and sample-processing procedures are designed and developed. Additionally, the curation team at JSC is investigating facility requirements, long-term preservation needs, storage requirements, and sample processing capabilities for cold conditions.

5.2.3 Sample Handling and Allocations

Given the anticipated annual cadence of missions that will involve sample return and the limited space in the sample handling facility, the traditional approach where each Apollo mission (except for Apollo 16 and 17, which have two each) has a designated glovebox is being re-examined (although the ultimate goal is to continue to use a separate, designated glovebox for each mission). A series of steps are being implemented by the curation team over the coming years to ensure the facilities are prepared for samples from the upcoming missions:

- The footprint for Apollo 16 and Apollo 17 will be reduced to a single glovebox each. The two extra gloveboxes will undergo the extensive approved cleaning procedures that are in place at JSC and will be designated to two Artemis missions instead.
- The glovebox currently used as a display case for visitors will be cleaned and repurposed as a designated glovebox for an Artemis mission.
- The curation team is investigating possibilities for utilizing the current core processing cabinet for processing of other non-core samples, adding additional cabinets to the pristine side of the lab.
- A triple processing cabinet will be procured and placed at the front of the lunar processing facility near the Visitor Viewing Area. This cabinet will be used to optimize workflow during preliminary examination, to ensure the 6-month catalog production schedule is met. After preliminary examination for a given mission is complete, the triple processing cabinet will undergo the extensive approved cleaning procedures that are in place at JSC in preparation for the next mission's preliminary examination phase.

Likely the greatest concern for the future of lunar curation and sample processing is the overall space currently dedicated to these activities at JSC as well as the aging infrastructure. There are numerous potential solutions that could be implemented; however, each one has a ripple effect and will impact other spaces (e.g., the return sample side, the lunar experimental laboratory, the thin section laboratory). The curation team is, and will continue to, work in close coordination with the Astromaterials Research and Exploration Science management and infrastructure teams at JSC to plan for lunar curation as part of the overall facility strategies.

5.2.4 Non-traditional Storage and Processing

Artemis samples are currently set to be processed under a nitrogen purge as is done with Apollo sample processing. There are additional scientific objectives (e.g., nitrogen isotopic compositions), however, that could be addressed if samples were curated under different or non-traditional ("special") conditions.

Future efforts through both community feedback (LEAG-ExMAG SAT) and advanced curation work should aim to answer questions, including:

- Are there science questions that could only be answered if materials are stored under “special conditions”?
- If so, what other “special conditions” should Artemis samples be curated under?
- How much material should be curated under these “special conditions”?
- What sample processing techniques need to be developed to process under these “special conditions”?
- What are the facility requirements to store and process samples under these “special conditions”?

5.3 Workforce Development

Two decades of studying the Moon, largely from orbit, has led to a vibrant and active lunar remote sensing and modeling community. There is also a small community that conducts laboratory studies and continues to study Apollo samples and lunar meteorites. The lunar community, however, must continue to grow and evolve to meet the needs of this era of lunar exploration. Specifically, remote sensing and modeling expertise must be retained, and the sample science, geophysics, in-situ science, and field geology communities must be strengthened in a thoughtful and forward-looking manner.

Inclusion, diversity, equity, and accessibility (IDEA) are at the core of all decisions that are being made for workforce development strategies and are interwoven into every step of planning for the future of lunar science and sample return efforts. Future expansion of the community is therefore an opportunity to also diversify the community in an equitable and accessible manner and in recent years, several new initiatives have been incorporated into ROSES and other SMD solicitations with such intent. These initiatives include:

- Requirements for inclusion plans in proposals to several ROSES elements, including PRISM;
- Requirements for Codes of Conduct in proposals to ANGSA and Solar System Exploration Research Virtual Institute (SSERVI) solicitations; and
- Requirement for a Community IDEA Plan in proposals to SSERVI solicitations.

Feedback and lessons learned from these initiatives are being incorporated to build on and improved these components for future calls. Similar efforts will be implemented, where appropriate, in future programs centered around lunar science.

NASA has been actively incorporating IDEA-efforts across all that we do, However, it is generally understood that scientists may not be best suited to create, improve, and maintain these efforts. Therefore, most of our future workforce development efforts will exploit and adapt the wealth of existing successful programs to best serve the lunar science community. For example:

- The Here to Observe (H2O) program that partners undergraduate students at non-R1 institutions with NASA mission teams. Following a successful pilot, in the program's next iteration, LRO will partner with a selected institution to continue to instill excitement for lunar exploration in the next generation of STEM leaders.
- SSERVI's Equity, Diversity, and Inclusion (EDI) Focus Group to support learning, sharing, and change across the lunar, asteroid, and human exploration communities. NASA continues to support the implementation of this focus group and encourages any interested parties to join the discussions.

Ensuring that the lunar science community continues to engage with other NASA or SMD-level programs is also a priority. Such opportunities include: the PI Launchpad, the SMD MOSAICS (formerly Bridge) Program, the National Consortium for Graduate Degrees for Minorities in Engineering and Science, and the Minority University Research and Education Partnerships (MUREP).

5.4 Research and Analysis Strategy for Lunar Science

NASA Research and Analysis (R&A) programs will play an important part in maximizing the science return of the investments in this era of lunar exploration. The general approach will be to supplement the available funding for existing programs, especially in areas (communities and capabilities) that require strengthening. In some cases, new research programs may also be developed to meet strategic needs.

5.4.1 Existing Research Programs

As NASA prepares for Artemis, and as new data become available from new lunar missions (CLPS, Lunar Trailblazer, etc.), high-priority research areas may be called out specifically in ROSES calls such as the Lunar Data Analysis Program (LDAP), the Planetary Data Archiving, Restoration, and Tools (PDART) program, the Laboratory Analysis of Returned Samples (LARS) program, and others. For example, LDAP has already been updated to note that CLPS data will be eligible, and LARS was updated for ROSES24 to specify the need for development of techniques for analyzing cold-curated samples. The budgets of both programs will be supplemented. Additional funding will also be made available for lunar-focused work in other ROSES calls. PSTAR will be updated in ROSES25 to allow for lunar analog work.

Selections were made for Solar System Exploration Research Virtual Institute (SSERVI) Cooperative Agreement Notice 4 (CAN-4) in May 2023, which was focused on lunar fundamental and applied research and specifically encouraged sample-focused science. Teams were selected that focus on a variety of lunar topics, including sample science, as well as various aspects of volatile science. All of the teams selected are focused on high-priority topics, e.g., as enumerated by OWL and the M2M Strategy. A draft CAN-5 is expected to be released for community comment in late 2024 and will also be lunar focused. SSERVI continues to be jointly funded by SMD and ESDMD and serves as an intersection and integrator between science and exploration. The CAN-4 SSERVI selections reflect a balance between science and exploration that is consistent with the relative contributions to SSERVI program funding from the mission directorates, as recommended by OWL.

In general, sample analysis proposals for any new returned lunar samples, whether through Artemis, CLPS, or any other mechanism, will be through ROSES via the LARS program. Apollo samples continue to provide new insights into lunar science decades after collection and we expect that much of the advancements in lunar science to be gleaned from Artemis will come from the analysis of those returned samples. The current LARS budget will be supplemented to meet the needs of the lunar community, while maintaining an appropriate balance with the other elements of the LARS portfolio.

5.4.2 New Research Programs

New programs will only be created when necessary (i.e., when existing calls do not meet specific needs) and their scope and duration will be clearly communicated. If timing allows, drafts of any new solicitations will be released for community comment before finalizing the text. Several new programs have already been implemented to meet the needs of the CLPS/Artemis era of exploration:

Development and Advancement of Lunar Instrumentation (DALI) – This is a mid-TRL technology development program. The goal of DALI is to mature instrumentation for all aspects of our lunar program, including orbital assets, CLPS and other landers, and human-deployed or -utilized instruments for Artemis. DALI is an annual solicitation, but its cadence and budget are regularly reassessed to ensure it is meeting current and future needs.

Payloads and Research Investigation on the Surface of the Moon (PRISM) – This program focuses on multi-instrument payload suites to be delivered to the lunar surface by CLPS landers.

Apollo Next Generation Sample Analysis (ANGSA) Program – The goal of the ANGSA Program is to maximize the science derived from samples returned by the Apollo Program in preparation for future lunar missions anticipated in the 2020s and beyond. There have been two ANGSA solicitations thus far: one in ROSES-18 and one in ROSES-22. We may utilize the ANGSA program, or a similar one, in the future to provide a mechanism to build, expand, and diversify the lunar sample science community while supporting high impact science on returned lunar samples.

Analog Activities – This program provides a venue to competitively select team members to serve in Science Evaluation Room (SER) roles during certain Artemis analog activities. These integrated analogs are where we define roles and requirements to help us prepare for Artemis EVAs. This is nominally an annual solicitation but is dependent on NASA’s need and plans for analog activities.

Lunar Mapping Program (LMaP) - This program element is intended to enable individual researchers to participate as a member of a geologic mapping team in the planning and execution of campaign-style mapping of selected regions of the Moon to support the construction of targeted, innovative, and content-diverse geologic maps that will aid in human lunar exploration. ROSES24 is a pilot program, but if successful, this is intended to be an annual solicitation.

Artemis Geology Team (AxGT) – This program will be the mechanism to onboard the geology team for each Artemis sortie-style mission. The team has been selected for the first of these solicitations (Artemis III).

Artemis Participating Scientist Program – In addition to the AxGT, we anticipate participating scientist solicitation for each mission as well to supplement and fill gaps in expertise.

Artemis Deployed Instruments (AxDI) – This program will be the mechanism by which instruments are solicited and selected for deployment on the lunar surface by Artemis crew. Deployed instruments will consist of autonomous instrument packages installed on the lunar surface by astronauts during EVAs and will address science objectives outlined in the Artemis III Science Definition Team (SDT) report and other community documents. Selections have been made for A3DI, Solicitations are anticipated for deployed instruments for each crewed Artemis landing.

Lunar Terrain Vehicle (LTV) Instruments Program – The LTV Instruments Program will solicit proposals for investigations that include a suite of science instruments that address decadal-level science objectives, for integration onto the LTV that is anticipated to be delivered to the surface in mid-2028. Proposals are due in December 2024.

Handheld Instruments – Instruments to be directly used by astronaut crew will be procured through requests for proposals (RFPs) for Artemis IV and future missions. These instruments will not have science teams; their use will be integrated into operations through the geology team. No handheld instruments are expected for Artemis III.

5.4.3 Laboratory Development

As the community's access to extraterrestrial materials via various sample return missions is increased and the ways in which samples are collected and curated is innovated, the infrastructure and laboratory needs are closely monitored. Two activities are underway to further understand the future laboratory needs as they pertain to lunar samples (e.g., cold-curated samples), a LEAG-ExMAG SAT and internally driven research at JSC. The LEAG-ExMAG SAT will provide feedback on various items such as whether the available laboratories are ready for additional lunar samples, what facilities are needed to maximize the science return on future returned lunar samples, and what facilities or technique developments are necessary to analyze samples that are returned cold. The curation team at JSC is utilizing the Planetary Exploration and Astromaterials Research Lab (PEARL) to "develop unique and custom vacuum extraterrestrial microenvironments to constrain lunar polar ice simulant geochemistry" (https://ares.jsc.nasa.gov/projects/simulants/dust-testing-facilities/johnson-space-center.html). The combination of community input and the results of experimental studies currently underway by the JSC curation team will provide a comprehensive view of the facilities and technique developments required to successfully analyze returned lunar samples.

The community is also encouraged to utilize the various research and analysis programs available to secure funding for their own facilities and technique developments. The currently designated program elements for these two activities are the Planetary Science Enabling Facilities (PSEF) program element and LARS. PSEF allows proposals for experimental and analytical research facilities that are made available to researchers funded by NASA. The intention of this program is to fund facilities housing combinations of equipment, instruments, infrastructure, and technical expertise capable of supporting the research of a broad user base performing research relevant to NASA. For additional information regarding the current facilities available, as well as frequently asked questions about facility and instrument funding, is at https://science.nasa.gov/researchers/planetary-science-enabling-facilities.

5.5 Data

In the new era of open science, data from NASA missions and research will be findable, accessible, interoperable, and reusable (FAIR). This includes dissemination and archival of all scientific mission data from instruments in a public-facing archive (e.g., the Planetary Data System) as soon as practicable, but no later than six months after receipt of data on Earth, as well as all other guidance provided in NASA's Science Information Policy (SPD-41a). NASA's science culture and policies aim to promote transparency, provide accessible and reproducible data, and contribute to the global scientific community's scientific discoveries. We further expect our international partners to adhere to the same standards.

Implementation plans for data are informed by community input and recommendations from numerous sources including: the Artemis III SDT report, the Planetary Data Ecosystem Independent Review Board report, the Lunar Surface Science Workshop (LSSW) on Foundational Data Products, recent community efforts, and the joint LEAG/MAPSIT Lunar Critical Data Products (LCDP) SAT. Some ongoing data-focused initiatives include the following.

5.5.1 Lunar Spatial Data Infrastructure (SDI) Community

Organized the USGS, at the request of NASA in response to finding #26 in the LCDP SAT report, the Lunar SDI began meeting regularly in November 2022. The group is comprised of subject matter experts from NASA, the USGS, and the larger planetary mapping community. The Lunar SDI Working Group is a voluntary cooperation between planetary community members, with the aim of evaluating existing spatial data and data standards for the Moon and assessing spatial data storage, acquisition, discovery, and use needs of the lunar community. The overarching goal of the Lunar SDI is to allow individuals who are not spatial data experts to use these data to the greatest extent possible, with the lowest possible overhead. This working group addresses spatial data complexities by defining policies and standards regarding data interoperability, data contribution, and the long-term maintenance for the benefit of all user communities.

5.5.2 Sample Data

NASA is committed to ensuring free, immediate, and equitable access to federally funded research, including laboratory data acquired though NASA-funded work on extraterrestrial samples. The Astromaterials Acquisition & Curation Office and the OSIRIS-REx team are working to further develop the Astromaterials Data System (AstroMat) as a repository for sample data and to ensure it will meet the needs of Artemis and CLPS sample return. AstroMat is a comprehensive data infrastructure that allows researchers to access, publish, and preserve analytical data collected on extraterrestrial samples, including those returned from the Moon. The LEAG-ExMAG SAT will provide community feedback on data system needs, as well as online curation resources.

5.5.3 Geologic Mapping

Geologic maps and derivative products are fundamental parts of an integrated science, exploration, and development effort and are critical tools that afford tangible, significant economic return on short- and long-term investments. The USGS leads planetary mapping efforts and NASA is working closely with the USGS to define a coordinated geologic mapping effort for the lunar south pole to address knowledge gaps and meet the needs of the science community and both human and robotic exploration. A coordinated and sustained Artemis-supportive geologic mapping effort of the Moon ensures that geologic maps are available at the right time, at the right scale, and with the right content to support short- and long-term exploration of the lunar surface.

5.6 Education and Public Engagement

NASA's overarching mission is to explore the unknown in air and space, innovate for the benefit of humanity, and inspire the world through discovery. Inspiration, through education and public engagement efforts, is thus an important aspect of our lunar science strategy. NASA's renewed focus on lunar exploration—specifically the return of humans to deep space and the lunar surface through Artemis—provides an incredible opportunity to reach new audiences and inspire the public. Indeed, one of the main rationales for returning to the Moon is to inspire a new generation of explorers: the Artemis generation. These endeavors, however, require continued support from Congress, policy makers, and the public. It is imperative that the goals and benefits of lunar exploration, including the importance of addressing lunar and planetary science questions, are communicated effectively to a variety of audiences.

Rather than develop an original set of education and public engagement goals and initiatives here, coordination across NASA (including ESDMD, the Science Engagement and Partnerships Division, other SMD divisions, the Office of Communications (OComm), the Office of STEM Engagement (OSTEM)) will ensure that lunar science and exploration messaging is unified and consistent, and that appropriate resources are available to educators, students, NASA personnel, and lunar/planetary science community members. Some specific efforts include:

- Ensure NASA's lunar science and exploration efforts are part of the national conversation and awareness (e.g., major media and news outlets; interviews, op-eds, features).
    - To include efforts to reach expanded audiences (e.g., Spanish-language content).
- Ensure appropriate educational resources and materials are created and maintained (that incorporate correct lunar science information).
- Empower NASA personnel and planetary/lunar science community members to be ambassadors to external audiences (e.g., outreach events).
    - To include creation of an online toolkit of resources for outreach materials, including PowerPoint templates/slides, talking points, etc.

5.7 Community Engagement

Community members are encouraged to engage with a variety of science-focused groups, including:

- The appropriate analysis/assessment group(s), AG(s), that most closely support their field(s) of interest. For lunar science, this could be the Lunar Exploration Analysis Group (LEAG), the Extraterrestrial Materials Analysis Group (ExMAG), the Mapping and Planetary Spatial Infrastructure Team (MAPSIT), and/or the Inclusion, Diversity, Equity, and Accessibility (IDEA) Cross-AG Working Group.
- The Planetary Science Advisory Committee (PAC). Meetings are open to the public, except under special circumstances, and the PAC is chartered to provide information and advice that may affect federal policies and programs.
- The National Academies Committee on Astrobiology and Planetary Sciences (CAPS) This committee provides an independent, authoritative forum for identifying and discussing issues in astrobiology and planetary science with the research community, the federal government, and the interested public.

In addition, direct community input on a variety of Artemis-related topics has been received and will continue to be sought through the virtual Lunar Surface Science Workshop series.

5.8 International Engagement

NASA's goal of returning to the Moon and continuing to Mars with commercial and international partners presents unique opportunities for advancing scientific objectives through global collaboration and commercial partnerships. International cooperation will not only leverage the expertise and resources of multiple nations but will also symbolize the peaceful pursuit of scientific knowledge and exploration beyond our planet.

NASA shares its architecture plans through the Architecture Definition Document (ADD) to capture the methodology, organization, and decomposition necessary to translate the broad scientific objectives outlined in the M2M Strategy into functions and use cases that can be allocated to implementable programs and projects. Inherent in this process will be the need to communicate the long-term vision, maintain traceability to responsible parties, and iterate on the architectural implementation as innovations and solutions develop. International and commercial partners are critical to addressing many of the M2M science objectives through innovative solutions from the commercial sector or international contributions reflecting their scientific core competencies. These partnerships may be enacted through direct, strategic cooperation or through solicited scientific investigations available to the global community.

For example, NASA is open to partnering with international agencies to conduct scientific investigations that specifically address national scientific priorities, as outlined in major community driven documents (e.g., Decadal Surveys, M2M objectives, etc.). Contributions from international partners and decisions on how to make the best use of scientific allocations on all mission platforms will be based on scientific merit and in alignment with U.S. science priorities and NASA science policies, and confirmed by peer-review panels. All foreign or domestic potential contributions will be subject to the same rigorous scientific merit evaluations.

NASA will endeavor to host forums that openly communicate objectives, plans, and opportunities to the broad global scientific and commercial communities. These forums will provide participation as well as opportunities for potential partners to provide input to NASA. Communication of NASA's goals will allow for open dialogue resulting in the optimization of resources, avoiding duplication of effort, and efficient use of partners' technology and associated expertise. International partners can participate in the International Space Exploration Coordination Group (ISECG) Science Advisory Group and are encouraged to participate in the ESDMD-led M2M workshops and Artemis Accords working groups.

NASA is also open to strategic partnerships that utilize international and commercial partners' missions and/or platforms to further the overall scientific goals of the Agency. Contributions of instruments, expertise, participating scientists, and/or data analyses can enhance any mission's success and impact on scientific discovery.

5.9 Sustainable and Responsible Use of Planetary Bodies

Many features of the lunar and martian surfaces are unique and should be protected and managed to maintain their pristinity for long-term scientific discoveries. Examples of these regions include the radio-quiet far side of the Moon, permanently shadowed regions at the lunar poles, and recurring slope lineae on Mars. NASA continues to seek input on how to explore responsibly and recently held a workshop on Artemis, Ethics and Society to solicit input from experts across a wide variety of disciplines.

International partners are expected to adhere to the principles of the Outer Space Treaty as well as those in the Artemis Accords to ensure responsible and ethical exploration of other planetary surfaces.

5.10 Mars-Forward Strategy

While exploring the Moon, NASA will prepare for and demonstrate capabilities relevant to human exploration of Mars. In order to fully realize the potential for using lunar exploration to prepare for Mars exploration with humans, Mars science objectives must be clearly defined, followed by identification of key capabilities that are also relevant to lunar exploration. There are a number of activities in work to establish the science objectives and associated capabilities, technologies, and operations that are relevant for operations on both the Moon and Mars. For example, as of 2023, the Mars Exploration Program Analysis Group (MEPAG) is updating their goals for Mars exploration, both with robots and with crew. LEAG and MEPAG are also in the process of formulating a joint study team(s) to complete a community-driven assessment for activities that can be demonstrated on the Moon, in preparation for crewed exploration of Mars.

These assessments will culminate in a series of National Academies studies NASA is requesting to help define a list of prioritized campaigns of human missions to Mars. The first requested study will focus on the cross-disciplinary science humans should address on the surface of Mars and the second will focus on the science humans should address during the in-space segments of the missions to Mars. In both cases, the study will consider which aspects of Mars exploration will benefit from lunar exploration. The Moon will continue to be a cornerstone for understanding the origin and evolution of the solar system and soon it will also be a cornerstone for learning how to live and work on another planetary surface in the modern era.

6 Additional Science Enabled by the Moon-to-Mars Strategy

Exploration Exploration at the Moon supports science in several disciplines outside of planetary science, as outlined here. ESSIO was created to ensure that science enabled by CLPS and Artemis across the SMD portfolio is coordinated and maximized. In addition to Planetary Science, Moon to Mars science objectives have been defined for BPS, Heliophysics, and Astrophysics. NASA will continue to refine and develop those objectives and our strategy to achieve them in light of the Decadal studies for the respective divisions.

6.1 Biological and Physical Sciences

Two goals of NASA's Moon-to-Mars strategy are "Advance understanding of how biology responds to the environments of the Moon, Mars, and deep space to advance fundamental knowledge, support safe, productive human space missions and reduce risks for future exploration." and "Address high-priority physics and physical science questions that are best accomplished by using unique attributes of the lunar environment." Biological and physical systems are affected by gravity and other environmental factors. Currently, research is conducted on the ground (1 g environment), on the International Space Station (micro-gravity environment), and will be conducted in a PRISM payload (Lunar Explorer Instrument for space biology Applications (LEIA)) and on Artemis missions and Gateway (microgravity environment plus deep space radiation). The plans of NASA's Moon-to-Mars architecture, including the transportation vehicles (Orion spaceship, human landing system) and Gateway, will provide access to additional gravity, radiation, and stress environments.

6.1.1 Biological Sciences/Space Biology

The Moon represents a critical location for building an accurate body of knowledge and representative models that enable scientists to understand and predict how biology functions, changes, acclimates, adapts, and survives in deep space and other non-terrestrial locations. An important knowledge gap that will be addressed by biological studies on and around the Moon is if partial gravity can recover and maintain normal physiological health and function, which is critical to understanding if the use of artificial gravity will be beneficial to human physiology for long-duration space travel in microgravity. For long-duration human habitation on the Moon and Mars, and in transit to Mars, investigations will be conducted to obtain data to understand how plants, especially crop plants, respond to and grow in partial gravity. Studies of deep-space radiation will also be conducted for basic science data that will enable space agriculture and associated technology development. The development of models for how the ecosystem of microbes on material surfaces change, survive, and interact with the humans and their microbiome will aid in identifying health countermeasures and materials resistant to microbial-based corrosion. Another important area of investigation is research about stress response and identifying underlying mechanisms of these responses, which will reveal how biology controls and adapts to the extreme environment of deep space, the Moon, and Mars.

Space biology research is expected to occur during individual sortie missions and across multiple mission durations, which includes uncrewed phases and operating through the lunar surface night. Experiments that occur over different timescales will follow how biology changes over time. All space biological studies will conduct control studies on Earth, with potential comparative studies in low Earth orbit. In the absence of vertebrate animals, tissue-on-a-chip will be used as an analog for human organs and multi-organ systems. Plant biology research will use a diversity of genetic plant models and crop plants. Microbiology studies will involve bringing microbes to the Moon and Gateway and sampling the microbes that are naturally living on the astronauts and elements of Artemis infrastructure.

6.1.2 Physical Sciences and Fundamental Physics

Many physical processes are affected by gravity. As in biological processes, gravity can mask some of the fundamental forces at work in these systems. When gravity is removed, for either a few seconds in a drop tower or for extended periods on the ISS, or decreased during Artemis missions, new physical processes are expected to be revealed. In addition to pushing the boundaries of fundamental research, some of the anticipated new knowledge is critical for future space exploration and its architecture.

Examples of important physical science investigations that are enabled by the Moon-to-Mars architecture include:

- Limited results from reduced gravity aircraft testing demonstrate that the lunar gravity of 1/6 g, in combination with the defined vehicle atmospheric pressure and oxygen percentage, represents a potential worst-case scenario for fire safety. In the case of an accidental fire, flammability and flame spread/heat release will be the highest at 1/6 g in the range between 1-g and zero-g.
- Fluids behave differently in a 1/6 g environment because the relationship among inertial, viscous, surface tension, and buoyancy forces are complex and nonlinear between 1-g and microgravity. Investigation at 1/6 g will allow investigators to understand the full continuum of the effect of gravity on fluid motion.
- The flow and aggregation of granular materials is affected by shape, static electric charge, composition, number of particles per unit volume, and the magnitude and direction of the gravity vector. Understanding granular flow at 1/6 g is required for effective in-situ resource utilization.

Experiments combining partial gravity, ultra-cold temperatures, the vacuum of the lunar surface, and the distance to Earth are some of the unique features that the Moon-to-Mars architecture enables for quantum mechanics investigations.

Undertaking basic research provides the knowledge needed to build practical systems for the human exploration of Mars. It also creates new knowledge that can be applied in the commercial space economy. Processes such as fuel management, manufacturing, construction, medicine, and agriculture rely on the knowledge gained through the biological and physical sciences research program.

6.1.3 Ongoing Investigations

The Decadal Survey in Biological and Physical Sciences in Space was released by the National Academies in Fall 2023. This document provides the recommendations and key scientific questions (KSQ) for biological,physical, and fundamental physicsresearch during the Artemis era. The Artemis III Science Definition Team Report provides some early objectives and priorities. NASA will continue to select investigations through open calls (like ROSES), directed work, and international collaborations.

NASA has already begun to expand its research beyond low Earth orbit and to the Moon. NASA flew experiments on Artemis I that included microbiology, plant seeds, and algae to investigate how the deep space radiation environment affected biology. It has examined plant growth in Apollo regolith to understand regolith composition effects on plant biology as a first step towards lunar agriculture. Studies using simulated partial gravity on ISS have been conducted for plants and rodent research to inform partial gravity research on the Moon. An experiment on NASA's CLPS lander CP-22 will study how partial gravity and radiation affects yeast biology, which is an analog of human radiation genetics and damage/repair responses. Ground studies were awarded for research using regolith simulants to obtain more baseline data on the impacts of regolith on rodent heath and plant growth and to inform future studies using Apollo- and Artemis-collected regolith. Finally, a new ROSES-competed experiment is planned for the surface of the Moon during Artemis III to study plant biology using a model of crop plants, which includes specimen return for detailed molecular analyses.

6.2 Heliophysics

One Goal of NASA's Moon-to-Mars strategy is to "Address high-priority heliophysics science and space weather questions that are best accomplished using a combination of human explorers and robotic systems at the Moon, at Mars, and in deep space." The capabilities of NASA's Moon-to-Mars architecture, including the Gateway space station, access to the lunar surface via Artemis missions, and more generally access to cis-lunar and deep space, can be utilized to advance high-priority heliophysics and space weather science objectives. High-priority heliophysics science objectives are set by the National Academies Decadal Survey in Solar and Space Physics.

Generally, all competitive science opportunities, including those solicited by the Space Weather Program, Living with a Star, and through PRISM, are open to proposed projects that can leverage the investments in the Artemis architecture and address the heliophysics science objectives called out in the Moon-to-Mars Objectives document. Current and past missions, such as LADEE, MAVEN, and ESCAPADE, have established firm baselines for future investigations, chosen through open competition, to build upon. The Heliophysics Environmental and Radiation Measurement Experiment Suite (HERMES) will be mounted on the outside of NASA's Gateway outpost; HERMES will contribute to addressing M2M objectives HS-1, HS-4, and AS-1. The THEMIS/ARTEMIS mission has two spacecraft in equatorial orbit at the Moon that will be used with HERMES to contribute to addressing objectives HS-1 and HS-4.

NASA will also take advantage of private and international missions to cislunar space for advancing the heliophysics science objectives. NASA is partnering with ESA on the Vigil mission, a heliophysics and space weather mission at the Earth-Sun L5 libation point.

A specific area of both basic and applied research that will be addressed is space weather. HERMES, and its application to objective AS-1, has already been mentioned. HERMES is part of a collaborative effort with the ESA Radiation Sensor Array (ERSA) and ESA/JAXA Internal Dosimeter Array (IDA) payloads to contribute to addressing objectives HS-1, HS-4, and AS-1. NASA has established a Moon-to-Mars Space Weather Analysis Office at GSFC. NASA will be soliciting "pipeline" investigations, through ROSES, to develop space weather instruments that can be launched as rideshare or hosted payloads. Through these efforts, NASA will develop the capabilities for Earth-independent space weather prediction to ensure the safety of both crew and infrastructure during the Artemis era.

6.3 Astrophysics

One Goal of NASA's Moon-to-Mars strategy is to "Address high-priority physics and physical science questions that are best accomplished by using unique attributes of the lunar environment." The astrophysics community identifies high-priority science questions through the National Academies Decadal Survey of Astronomy and Astrophysics and other science planning processes. All competitive science opportunities, including Explorers, Pioneers, and PRISM, are open to proposed projects that can leverage the investments in the Artemis architecture. Through peer review, the best science will be selected independent of proposed location. NASA will continue to study new mission concepts to determine whether the Moon represents a feasible or superior location for a high priority astrophysics investigation. When the best science can best be accomplished from or near the Moon, then astrophysics projects leveraging the Artemis capabilities will be initiated.

One objective (PPS-1) is to "Conduct astrophysics and fundamental physics investigations of space and time from the radio quiet environment of the lunar far side." Several radio astronomy experiments have been selected to be placed on the Moon as part of the CLPS program; the first two are (i) the Radio-wave Observations at the Lunar Surface of the photo Electron Sheath (ROLSES) experiment that flew on the CLPS IM-1 mission in 2024 and that will fly on the CLPS Task Order CP-21 mission to the Gruithuisen Domes in 2028 and (ii) the Lunar Surface Electromagnetic Explorer-Night (LuSEE-Night) mission, conducted in partnership with the Department of Energy and planned for delivery to the Moon on the CLPS CS-3 mission in 2025. LuSEE-Night is a pathfinder mission to land a radio telescope on the far side of the Moon and take the most precise measurements of the sky at frequencies below 50MHz. NASA has studied several concepts for lunar far side radio observatories including Farside Array for Radio Science Investigations of the Dark ages and Exoplanets (FARSIDE) which could measure the fundamental physics processes occurring during the epoch prior to the formation of the first stars and galaxies.

LuSEE-Lite, flying on CLPS Task Order CP-12 to Schrodinger Basin, is a variation on LuSEE-Night that will use plasma wave measurements to characterize the lunar ionosphere and the interaction of the solar wind and magnetospheric plasma with the lunar surface and crustal magnetic fields.


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7 Summary and Next Steps

This is an exciting era for lunar exploration; not since the days of the Apollo Program has the world been so focused on the Moon. This Implementation Plan outlines the efforts NASA is making to ensure that the lunar science community is prepared to take advantage of the increased access to the Moon provided by CLPS and Artemis, and to build a strategy ensuring that the highest science priorities of the community are addressed.

As discussed throughout this Implementation Plan, there are several actions being taken in the near term (~2 years) to acquire the information and data needed to continue to build and define this strategy.

- Fund a short study to further define the rover requirements and potential payloads of the Endurance-A concept. This effort includes gathering community input, to better define the science objectives (Section 4.1).
- Develop a South Pole Aitken sample Return and eXploration Science Definition Team (SDT) to further flesh out the science objectives and measurement requirements of such a mission (Section 4.1).
- Conduct a LGN payload study to explore the requirements and feasibility of a CLPS-based approach (Section 4.2)
- Contract the National Academy of Sciences to conduct a study on the Key Non-Polar Destinations Across the Moon to Address Decadal-level Science Objectives with Human Explorers (Sections 4.1, 4.4).
- Contract the National Academy of Sciences to conduct a study on the science objectives that can be achieved in the sustained phase of lunar exploration (Sections 4.1, 4.4).
- Conduct a pre-phase A study on “LExSO” (Lunar Exploration Science Orbiter) using the LEAG CLOC-SAT report as a guide (Section 3.2)
- Request a joint LEAG/ExMAG study on Artemis Samples, including panels on volatile as well as non-volatiles samples and sample data (sections 4.3, 5.2, 5.5).
- Work with the USGS to define a coordinated geologic mapping strategy for exploration of the south pole (Section 5.5).
- Continue community engagement on the evolving Moon to Mars Definition Document (Section 1).
- Continue the Lunar Surface Science Workshop series to acquire direct feedback on topics important to the science community (Section 5.7).

This Implementation Plan will be updated on a roughly biannual basis and will incorporate the results of these and other efforts as our capabilities evolve. Several more CLPS landings are expected to be completed within the next two years, which will allow for a more detailed CLPS strategy to evolve ahead of the next Implementation Plan revision. Similarly, the Artemis architecture will have matured further, including the expected launch of Artemis II, allowing increased definition of our Artemis science strategy. Over the next two years, additional strategic planning efforts will focus on technology development and interactions with our international partners.

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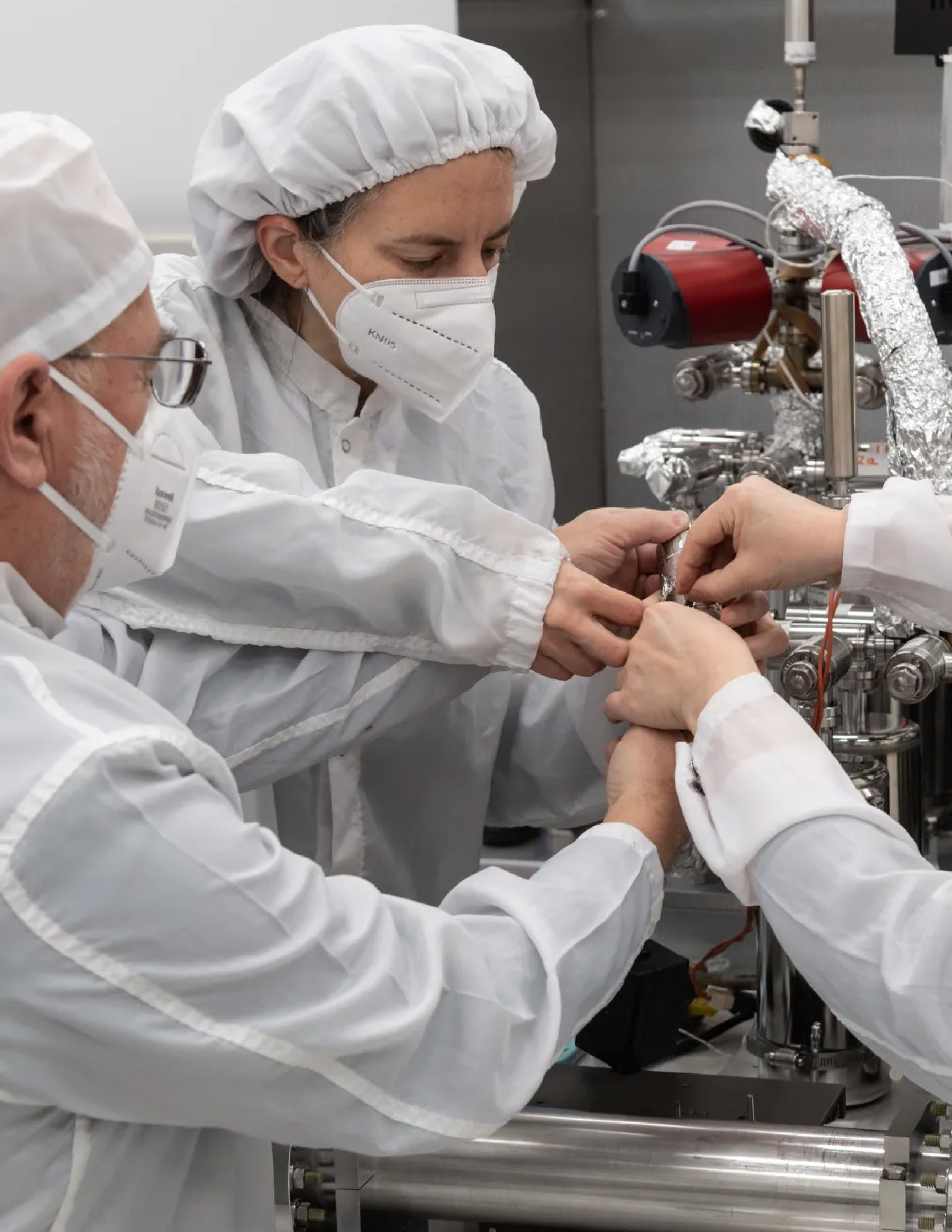
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