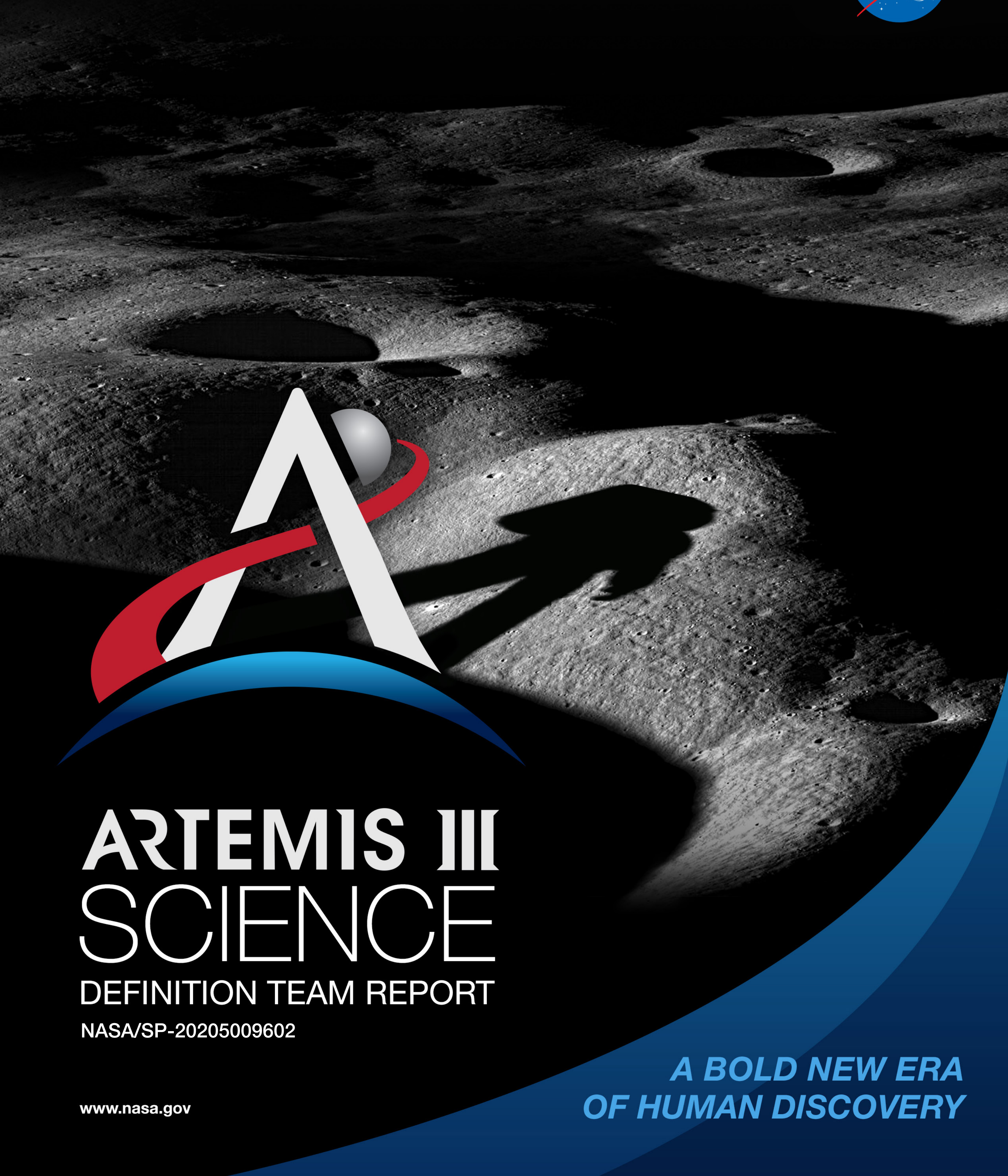
National Aeronautics and Space Administration



ARTEMIS III SCIENCE

DEFINITION TEAM REPORT

NASA/SP-20205009602

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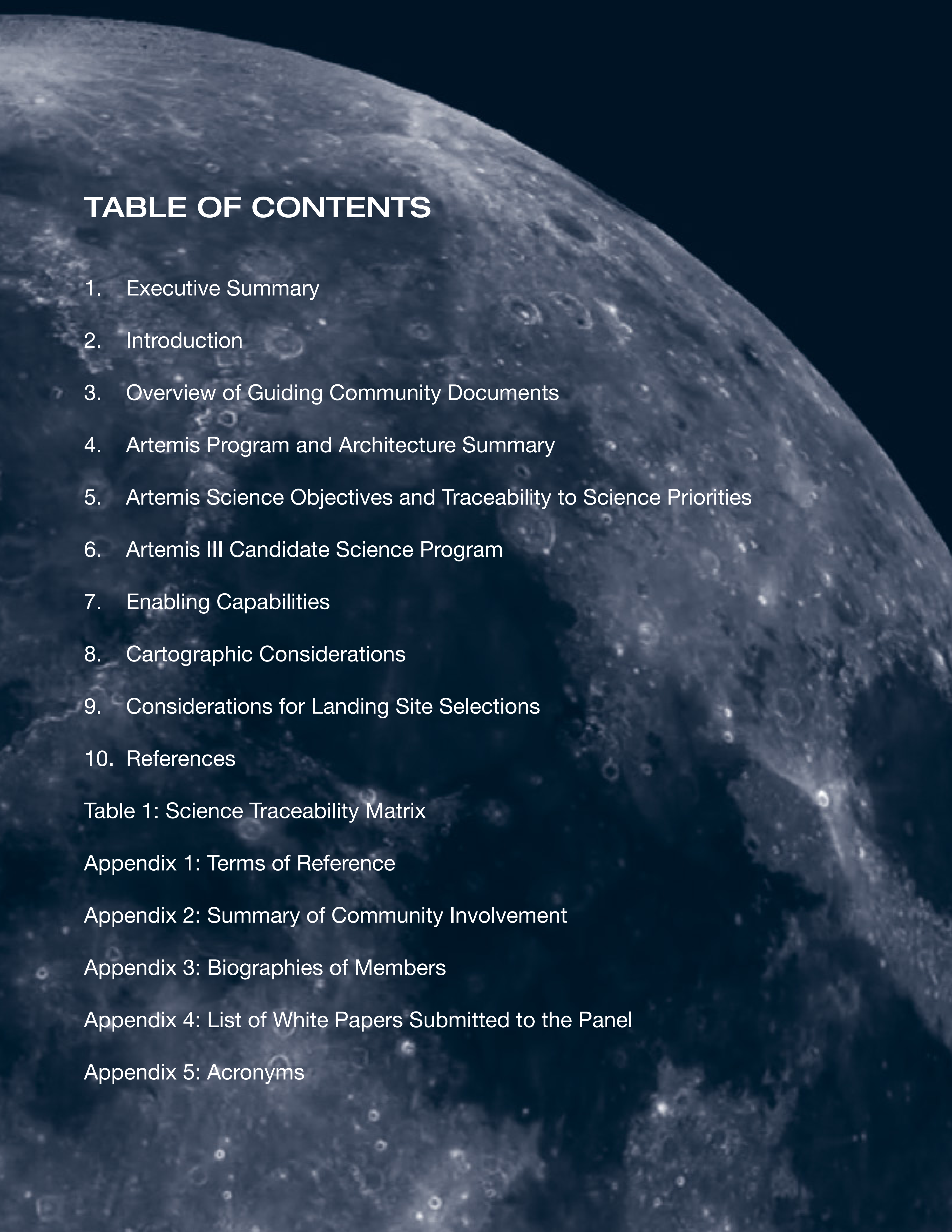
A BOLD NEW ERA OF HUMAN DISCOVERY



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SECTION 1

EXECUTIVE SUMMARY

Artist's rendering of an Artemis III EVA. The first human mission to the Moon in the 21st century will be the start of a bold and inspiring journey of human discovery into our Solar System.
Credit: NASA

1. Executive Summary

The Artemis III mission will be the first human mission to the surface of the Moon in the 21st Century, and will build on the legacy of Apollo to usher in the modern era of human exploration and development in deep space. The lunar surface is an ideal location to answer fundamental planetary science questions. In the 50 years since humans last visited the Moon, new advances arising from robotic lunar missions, reanalysis of older data, modeling, and sample analysis have produced dramatic results and new questions about planetary volcanism, volatiles, impact processes, tectonics, and the lunar environment. Driven by new questions, we set out a robust science plan for the Artemis III crew return to the lunar surface.

Seven overarching Artemis III Science Objectives have been defined by the Science Mission Directorate in the Artemis Science Plan (Section 2.1) and form the foundation of the Science Definition Team's consideration. Expanded to encompass the full range of science goals identified in our Guiding Documents and submitted white papers, they are:

- Understanding planetary processes
- Understanding the character and origin of lunar polar volatiles
- Interpreting the impact history of the Earth-Moon system
- Revealing the record of the ancient sun and our astronomical environment
- Observing the universe and the local space environment from a unique location
- Conducting experimental science in the lunar environment
- Investigating and mitigating exploration risks

The Science Definition Team substantiated these Objectives with Goals and Investigations identified by the community over the last decade in guiding documents and current white papers (Section 5). The team's goal was to be as inclusive as possible in this effort, so that the scope of science that is of interest to the community is clear, and so that future human missions beyond Artemis III can build on the completed Investigations towards a more robust scientific understanding. The Investigations were then prioritized based on the community-authored Guiding Documents, and the team's assessment of compelling science questions that could be realistically executed during the Artemis III surface mission.

From these Investigations, the Science Definition Team built a candidate reference program that would capture the highest-priority science for Artemis III and provide the greatest feed-forward to follow-on missions and the ultimate build-up to the Artemis Base Camp. Activities related to field geology, sample collection and return, *in situ* and field science, and deployed experiments are needed for a cohesive program. This candidate set of activities, taken collectively, will address both the highest investigation priorities as well as a multitude of additional Investigations. It is expected that a more detailed mission operations plan will need to be developed by NASA when HLS system capabilities, a landing site, and other architectural details come into sharper focus.

With this notional program, mission planners can weigh operational constraints to develop a science implementation plan for the mission, including the collection of samples, deployment of instruments, and key *in situ* observations by the crew. Procedures and operations techniques, particularly for sample acquisition and curation, developed for the Artemis III mission will influence future Artemis missions, research activities and operations at the Artemis Base Camp, and future expeditions to Mars. The transformational planetary science knowledge resulting from the Artemis III mission will also provide new discoveries that will be important for understanding other planets and small bodies in the inner Solar System. The Moon is a spectacular world full of wonder and opportunity that is only a few days away. With its tremendous bounty of accessible resources, stunningly beautiful vistas, and compelling scientific questions, the Moon continues to beckon us towards the next horizon as the gateway to the rest of our Solar System.

1.1 Findings and Recommendations

Findings and recommendations resulting from this Artemis III Science Definition Team activity are collected here and numbered according to the sections of the report whence they originated.

Finding 6.1.4-1: The optimal sample return program is built upon geologic-context observations made by well-trained astronauts, aided by modern tools and real-time communication with scientists on Earth.

> **Recommendation 6.1.4-1:** Astronauts should participate in an Apollo-style course in geology and planetary science, including both field and classroom components, in order to provide optimal *in situ* geologic characterization of lunar sample collection sites. A dedicated team of scientists should serve in an Earth-based Artemis III Science Mission Center with real-time two-way audio and one-way video between the crew and the Science Mission Center.

Finding 6.1.4-2: The high-priority Investigations described in this report require the collection of a diverse set of sample types, collected from geographically diverse locations broadly representative of the complex geology of the south polar region, and a total return sample mass from the Artemis III south polar site exceeding the average return mass for the Apollo missions.

> **Recommendation 6.1.4-2:** Astronauts should be trained and equipped to collect a variety of surface and sub-surface samples. NASA should plan to return total sample masses in excess of previous lunar sample return missions.

Finding 6.1.4-3: Sample collection and *in situ* measurement campaigns are complementary and increase science return.

> **Recommendation 6.1.4-3:** NASA should ensure that sample collection and *in situ* measurements are carefully choreographed to maximize science return. Examples of such coordination include the characterization of rock samples with *in situ* instrumentation to aid in prioritization of samples selected for Earth return, and *in situ* volatile measurements made in conjunction with sample collection to characterize volatile losses from sample collection, transport, and/or curation, and efforts to provide “ground truth” for orbital remote sensing datasets.

Finding 6.1.4-4: The return of hermetically sealed volatile bearing samples from the lunar south polar region can preserve lunar volatile signatures within the sample containment system and prevent gas-exposure hazards in the crew cabin.

> **Recommendation 6.1.4-4:** NASA should focus on the development of lightweight, double-sealed vacuum containers to return volatile bearing lunar samples to Earth. Minimizing the mass penalty for vacuum-sealing any given sample results in increased scientific yield of the mission since more mass can be allocated to the lunar samples instead of the sampling hardware.

Finding 6.2.4-1: Geophysical and environmental monitoring are needed to address multiple Artemis III Objectives.

> **Recommendation 6.2.4-1a:** The Artemis III mission is an opportunity lost if the first of a series of geophysical and environmental network nodes is not deployed. While incremental science can be obtained with short-lived experiments, long-lived power and communication capability will be required to fully enable prioritized investigations (see Section 7.1). The Artemis III node can be augmented by both robotic and human future missions, thus building towards a global network.
>
> **Recommendation 6.2.4-1b:** Geodetic monitoring via Earth-based laser ranging requires no lunar surface power or communication to function and hence will provide science return even in the absence of such capabilities. We advocate for geodetic monitoring capability to be prioritized for Artemis III.

Finding 6.3.7-1: *In situ* instrumentation will be greatly beneficial in addressing a number of Artemis III science investigations, including instrumentation to support sampling, volatile monitoring, geophysics objectives, down hole monitoring, and geotechnical characterization.

> **Recommendation 6.3.7-1a:** NASA should ensure that *in situ* imaging and assessment capability is available to crews during extravehicle activity (EVA) to document site characteristics, sampling, and instrument deployment.
>
> **Recommendation 6.3.7-1b:** We recommend NASA provides a mission capability of real-time transmission of data from *in situ* science instrumentation that provides documentation for site characteristics and enables a science support team (backroom, operations center, etc.) to support EVA operations with (near) real-time feedback to the crew when necessary on science decision-making, as well as provide processed data when necessary (i.e. helping convert raw data into tactical decision-making). This requires prior establishment of high bandwidth communication that is capable of extensive real-time data transmission to accommodate use of valuable measurements from modern sensors.

Finding 6.4-1: Existing mass allocations expected to be available on the human landing system (HLS) system for delivery of tools and payloads to the lunar surface are insufficient to achieve the full spectrum of science objectives outlined by the stakeholder community.

> **Recommendation 6.4-1:** NASA should solicit the development of instruments that are capable of addressing more than one measurement need and/or science Investigation.
>
> **Recommendation 7.2-1:** NASA should consider pre-positioning science assets in the vicinity of the Artemis III landing site. This could consist of an inert cache of tools/instruments to be accessed by crew upon arrival, and/or one or more instrumented landers or rovers for environmental monitoring.

Finding 6.5-1: In light of the importance of the Artemis III scientific results towards implementation of commercial resource extraction strategies and the construction of the Artemis Base Camp, efforts should be maintained to promote cross-directorate integration between the diverse stakeholders within NASA in the Human Exploration and Operations Mission Directorate (HEOMD), Science Mission Directorate (SMD), and the Space Technology Mission Directorate (STMD), and in the external scientific, engineering, and commercial communities.

> **Recommendation 6.5-1a:** A standing working group comprising scientific leadership of the Artemis program in SMD should be established and closely coordinate with representatives of STMD and HEOMD to ensure clear lines of communication and facilitate program implementation.

> **Recommendation 6.5-1b:** NASA's existing Program Analysis Groups, such as the Lunar Exploration Analysis Group (LEAG) and the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM), serve an important role synthesizing community input across diverse stakeholders in the engineering, science, and commercial communities, and should be leveraged as the program continues to promote external community engagement to the fullest practical extent.

Finding 7.1-1: Several of the Investigations prioritized in this report would be maximally enabled by a long-lived power source and communications capability for deployed experiments.

> **Recommendation 7.1-1:** NASA should pursue solutions for long-lived power and communications to enable networked operation of Apollo Lunar Surface Experiment Package (ALSEP)-like packages at multiple landing sites, as needed, to enable meaningful progress on many of the Goals described in Section 5, and feeding forward to future Artemis missions.

Finding 7.3-1: Crew mobility on the lunar surface is a key factor for enhancing the scientific Investigations outlined in this report.

> **Recommendation 7.3-1:** NASA should include a rover or other mobility solution for crew use on the lunar surface starting as early in the Artemis program as possible, ideally for Artemis III.

Finding 7.4-1: The ability to conduct cryogenic sample return from the Moon increases the scientific yield of samples containing icy and/or volatile components.

> **Recommendation 7.4-1:** NASA should develop and implement the required hardware and operations to return a subset of the samples at temperatures low enough to preserve water ice and other low temperature volatiles of interest, including non-H_2O volatiles, in the solid state throughout the entire journey from the lunar surface to Earth-based laboratories. Cryogenic sample return will increase the scientific fidelity of sample analyses of volatiles and ices. Minimizing the mass penalty for cryogenic sample return results in increased scientific yield of the mission because more mass can be allocated to the lunar samples instead of the sampling hardware.

Finding 8.2-1: Accurate geodetic control of data has a direct impact on the accuracy of spatial data analysis and intercomparison of data products, which is vital both to mission planning and scientific analysis.

> **Recommendation 8.2-1:** Any needed updates to the standard lunar geodetic coordinate reference frame (e.g., currently used by the Lunar Reconnaissance Orbiter (LRO)) should be identified in 2021, and foundational products should be mapped onto it and/or developed to

use it directly. Establishing a standardized coordinate reference frames can significantly improve data reliability and reduce the risk of errors.

Finding 8.2-2: Standardization of cartographic and timing parameters is vital for interrelating the timing of crew activities and the timing of measurements from instruments.

Recommendation 8.2-2: Standards for cartographic and time controls for surface measurements (photographs, video, and surface measurements) should be defined in the near term so that those standards can be implemented in instrument development. This should also include high-fidelity time coding for all surface measurements time-synced with Earth in UTC.

Finding 8.3-1: During preparations for Artemis III, existing lunar data should be readily and easily available to scientists and mission planners. Accurate landing and localization during surface operations are dependent on the accurate and robust use of existing data.

Recommendation 8.3-1a: We recommend maintaining sufficient funding to the Planetary Data System (PDS) to maintain the online tools needed to search, access, and use lunar data.

Recommendation 8.3-1b: To support the level of accuracy and precision needed for landing and surface operations, new cartographic products, including mosaics and topographic models, for the south pole should be developed using the highest quality data available (e.g., LRO NAC and LRO WAC frames, SELenological and Engineering Explorer (SELENE) Terrain Camera (TC), SELENE Multi-band Imager (MI), and Chandrayaan-1 Moon Mineralogy Mapper (M3)) and using the standard (possibly updated) lunar geodetic coordinate reference frame.

Recommendation 8.3-1c: New derivation of higher-order data products from existing missions should also be supported where needed for Artemis III. For example, it is vital that more detailed geologic mapping of candidate landing sites be accomplished at a scale similar to what was done in preparation for Apollo.

Finding 9.1-1: The scientific return of the Artemis III mission will be intrinsically linked to the Artemis III landing site.

Recommendation 9.1-1a: Science outcomes of this report should be an important consideration during the site selection process for the Artemis III mission.

SECTION 2

INTRODUCTION

The modern era of lunar exploration will dramatically improve our understanding of the Earth, Moon, and inner Solar System. Here, the Earth is straddling the limb of the Moon, as seen from above Compton crater. The large tan area in the upper right is the Sahara desert, and just beyond is Saudia Arabia. The Atlantic and Pacific coasts of South America are visible to the left. WAC E1199291151C (Earth only), NAC M1199291564LR (Earth and Moon); sequence start time 12 October 2015 12:18:17.384 UTC.

Credit: NASA/GSFC/Arizona State University

2.0 Introduction

In 2019, we celebrated the fiftieth anniversary of the Apollo 11 mission, humanity's first crewed journey to another world. The experience gleaned from the six Apollo expeditions from 1969-1972 – collectively, the field geology, the establishment of experimental packages on the Moon's surface, and the samples brought to Earth for analysis – redefined our understanding of the Solar System. In the 21st century, there has been a resurgence of international interest in the Moon, including the SELenological and Engineering Explore (SELENE) mission by the Japan Aerospace Exploration Agency (JAXA); the Chandrayaan-1 mission by the Indian Space Research Organization (ISRO); four Chinese missions: two orbiters (Chang'E-1 and -2) and two landed missions with rovers (Chang'E-3 and -4); as well as five NASA missions: the Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun (Time History of Events and Macroscale Interactions during Substorms (THEMIS)-ARTEMIS), the Lunar Reconnaissance Orbiter (LRO), the Lunar Crater Remote Observation Sensing Satellite (LCROSS), the Lunar Atmosphere and Dust Environment Explorer (LADEE), and the Gravity Recovery and Interior Laboratory (GRAIL). These 21st century results demonstrate that the Moon is not a barren and dormant world – it is a world with unparalleled opportunities for new scientific discovery, and rich opportunities for commercial activity (Keller et al., 2016; LEAG, 2016; 2017a,b; 2018). Breakthrough discoveries from Chandrayaan-1, LRO, and LCROSS – especially those regarding volatiles – have reinforced the Moon's status as a cornerstone of planetary science, and increased the necessity for a comprehensive program of lunar exploration and utilization that will drive economic growth, promote international collaboration, and expand human knowledge.

On 4 September 2020, the Associate Administrator of the Science Mission Directorate (SMD), Dr. Thomas Zurbuchen, established an Artemis III Science Definition Team to establish prioritized science activities for the Artemis III mission, the first human mission to the Moon in the 21st Century. These prioritized science activities were deemed essential information needed on an expedited basis to inform the ongoing Human Landing System (HLS) development activities underway in the Human Exploration and Operations Mission Directorate (HEOMD). Once established, the Science Definition Team (SDT) proceeded to execute a complete assessment of science objectives for the Artemis III mission, based on the existing Artemis Science Plan (Section 2.1), and implemented a comprehensive community engagement strategy (Appendix 2). It is intended that this report will provide the definitive statement of Artemis III mission priorities in the context of the exploration architecture, while providing a framework that can be built upon for subsequent Artemis missions. This report presents the outcome.

2.1 The Artemis Science Plan

NASA's Science Mission Directorate is leading the formulation of the Artemis Science Plan, outlined here in NASA's Lunar Exploration Program Overview. As part of the Artemis Science Plan, SMD developed overarching science objectives for the entire Artemis program, defined here to include all Artemis missions up to and including activities at the Artemis Base Camp. The Artemis Science Plan objectives are:

- Understanding planetary processes
- Understanding volatile cycles
- Interpreting the impact history of the Earth-Moon system
- Revealing the record of the ancient Sun
- Observing the universe from a unique location

- Conducting experimental science in the lunar environment
- Investigating and mitigating exploration risks to humans

These science objectives were developed by established community priorities, including those in the 2013-2023 Planetary Decadal survey (NRC, 2011), the 2007 National Research Council (NRC) Report on the Scientific Context for the Exploration of the Moon (NRC, 2007), the Lunar Exploration Roadmap maintained by the NASA Lunar Exploration Analysis Group (LEAG, 2016), the LEAG Next Steps on the Moon Report (NEXT-SAT, 2018), and the 2018 LEAG Advancing Science of the Moon Report (ASM-SAT, 2018). These reports all consistently outlined the incredible science value of a robust lunar exploration program that can address major outstanding science questions about the Moon and Earth, with numerous opportunities to impact our understanding of the Solar System, the Universe around us, and our place within it.

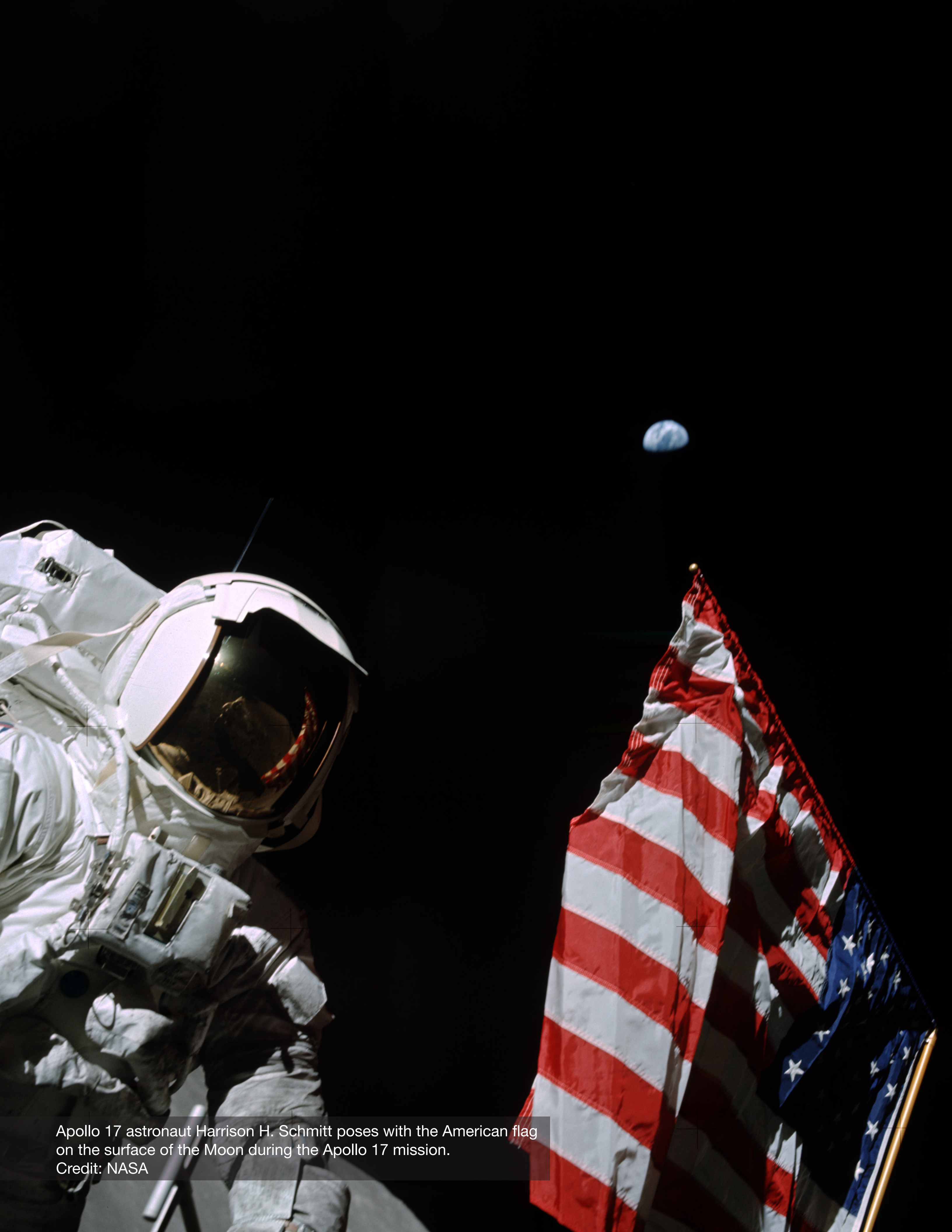
NASA intends to foster research in the broader scientific community by creating lunar investigation opportunities associated with the Artemis program, which will include competitive selection programs and open data policies. Achieving these research goals will require a coordinated effort among NASA's mission directorates to ensure that these high-level goals are met in a flexible and sustainable manner, all while leveraging the full capabilities of the domestic and international research communities. SMD is leading development of scientific activities in the areas related to field geology, sample collection and return, tools and instrumentation, access to previously unexplored cold traps, and missions to the lunar far side. Creating a pathway to advance low-technology readiness level (TRL) components and sensors is also part of the Artemis program, in order to enable human and human-robotic science.

The nature of science is iterative. The Artemis III mission, a single mission to the lunar surface, is only a beginning. Artemis III will not address each of the Artemis Science Plan objectives, and it won't address every open science question about the Moon – but it will be a firm foundation for future discovery. Artemis III and subsequent Artemis missions will reach the lunar surface and conduct field work and fundamental research that will answer longstanding planetary science questions and redefine our understanding of the Solar System. Furthermore, crews on the surface can collect data that complement data collected in orbit around the Moon on Gateway and in orbit around the Earth on the International Space Station (ISS), enhancing insight into the solar wind and radiation characteristics of these very different environments, as well as how these environments affect biological, human, and physical properties and responses. As a result, new hypotheses and research goals will arise, evolve, and become reflected in updated community science priorities. Addressing these new questions will benefit from the regular, sustained access to the lunar surface provided by the Artemis program, and Artemis III will be only the first in this new era of sustained exploration.

Ultimately, the Moon is a resource-rich, readily accessible target for future United States human and robotic missions that will enable fundamental scientific advances impacting our understanding of the Solar System and the Universe around us, enable commercial opportunity, increase our space-faring capability, and in so doing promote an enduring human presence beyond low-Earth orbit. The Artemis program, which will establish 21st-century American access to the lunar surface, will achieve a variety of ambitious science activities that will spur a new era of human discovery. It is expected that discoveries made on the Moon will have dramatic impacts on our understanding of the entire Solar System. The Artemis III mission will be the first steps on a bold and inspiring journey of human discovery.

SECTION 3

OVERVIEW OF GUIDING COMMUNITY DOCUMENTS



Apollo 17 astronaut Harrison H. Schmitt poses with the American flag on the surface of the Moon during the Apollo 17 mission.
Credit: NASA

3.0 Overview of Guiding Community Documents

The Apollo Program planned to conclude with Apollo 20 in the 1974 timeframe, after which NASA planned an ambitious set of follow-up missions to the lunar surface. These missions could have included longer stay times, pressurized rovers, pre-placed logistics, and permanent surface installations (a set of activities usually termed the Apollo Applications Program, AAP) (Hess, 1967; Shayler, 2002). Ultimately, budget reductions and changing national priorities resulted in the cancellation of Apollos 18-20 and all of the more ambitious AAP missions to the lunar surface in the 1970s, ending the first great era of lunar exploration. Active planning for human lunar missions resumed in the early 1980s because the National Space Transportation System could have been used to mount human lunar surface missions (Mendell et al., 1984). These planning activities resulted in a conference ("Lunar Bases and Space Activities in the 21st Century", W. W. Mendell, editor, 1985), which then proceeded into a series of studies, exploration initiatives (the Space Exploration Initiative, the Vision for Space Exploration, and now Artemis) and strategic planning exercises, including:

- The Report of the National Commission on Space (1986) [Paine Commission Report];
- The Report from the Lunar Geoscience Observer Workshop (1986);
- The Status and Future of Lunar Geoscience (1986);
- Leadership and America's Future in Space (1987) [Ride Commission];
- A Site Selection Strategy for a Lunar Outpost: Science and Operational Parameters (1990);
- Geoscience and a Lunar Base: A Comprehensive Plan for Lunar Exploration (1990);
- A Planetary Science Strategy for the Moon by the Lunar Exploration Science Working Group (1992);
- Lunar Surface Exploration Strategy (LExSWG, 1995);
- New Frontiers in the Solar System: An Integrated Exploration Strategy (2003) [2003-2013 Planetary Decadal Survey];
- A Renewed Spirit of Discovery: The President's Vision for US Space Exploration (2004);
- A Journey to Inspire, Innovate, and Discover (2005) [Aldridge Commission Report];
- Solar and Space Physics and its Role in Space Exploration (NRC Report) (2004);
- US National Space Policy (2006);
- New Views of the Moon (2006);
- LEAG Habitation Specific Action Team [HAB-SAT] (2005);
- LEAG Themes, Objectives, and Phasing Specific Action Team [TOP-SAT] (2005);
- Proceedings of the Conference on Astrophysics Enabled by the Return to the Moon (2006);
- LEAG Geology-Geophysics Specific Action Team [GEO-SAT] (2006);
- The Global Exploration Strategy: The Framework for Coordination (2007);
- National Research Council: The Scientific Context for Exploration of the Moon (2007);
- NASA Advisory Council Workshop on Science Associated with the Lunar Exploration Architecture, Tempe, AZ (2008);
- Vision and Voyages for Planetary Science in the Decade 2013-2022, NRC (2011) [2013-2022 Planetary Decadal Survey];
- LEAG Robotic Campaign Analysis Letter (2011);
- The LEAG Lunar Exploration Roadmap (2012-Present);
- The LEAG-International Space Exploration Coordination Group (ISECG) Volatiles Special Action Team (2014);
- The LEAG-ISECG Volatiles Special Action Team 2 (2017a);
- Next Steps on the Moon Specific Action Team [NEXT-SAT] (2017b);
- LEAG Back to the Moon Report (2017c);

- LEAG Advancing Science of the Moon Specific Action Team [ASM-SAT](2018a);
- Lunar Science for Landed Missions Workshop Report (2019) ;
- The LEAG Volatile Viability Measurement Special Action Team [VVM-SAT] (2018b);
- Lunar Dust and Its Impact on Human Exploration: A NASA Engineering and Safety Center (NESC) Workshop (Winterhalter et al., 2020);
- Global Exploration Roadmap v. 3.1 (2020); and
- Community white papers solicited for this Science Definition Team (SDT) (Appendix 4).

Thus, the current Artemis program is strongly buttressed by over four decades of richly detailed strategic planning efforts involving NASA program advisory committees, the National Academies of Science and Engineering, NASA internal actions, Presidential commissions, international coordination groups, and scientific and engineering community groups that have clearly and consistently stated and restated cohesive goals for United States lunar exploration efforts. Each of these activities has clearly articulated the value of lunar exploration for a variety of stakeholders, including the key role played by lunar exploration in scientific discovery.

For the purposes of the Artemis III mission Science Definition Team, the terms of reference identified four community consensus reports as a basis for its deliberations. Each of these community reports had already been playing an active role in the Artemis program definition since the start of the program.

The 2007 National Research Council “Scientific Context for the Exploration of the Moon Report” (hereafter, SCEM Report) was commissioned by NASA’s Science Mission Directorate in 2006 in the context of the Vision for Space Exploration. The VSE started in 2004 to establish a permanent United States presence on the Moon as the first step of an orderly progression of activities designed to use lunar resources to open up the Solar System to human activity. The SCEM Report was commissioned to capture the state of knowledge of lunar science and identify the most pressing new scientific investigations, which could then be used as a basis for defining and prioritizing activities within a human lunar exploration program. Some objectives outlined by the SCEM report were addressed by subsequent orbital missions (LRO, GRAIL, LADEE, and LCROSS). However, because no surface exploration missions (soft landers or rovers) were executed under the Vision for Space Exploration, a subsequent review (LEAG, 2018) indicated that the overall themes, objectives, and prioritization of the SCEM Report remained largely valid.

The NASA Lunar Exploration Analysis Group (LEAG) was established in 2004 and charged with organizing and leading the lunar exploration community, and supporting NASA mission objectives by providing objective analysis of scientific, commercial, technical, and operational issues to further lunar exploration objectives. LEAG reports to the Science Mission Directorate but also supports the objectives of the Space Technology Mission Directorate and the Human Exploration and Operations Mission Directorate, building bridges between science, exploration, and commerce whenever and however possible. LEAG has a standing Commercial Advisory Board (CAB) to offer programmatic insights into the capabilities provided by industry. LEAG is a community-based, volunteer-driven, interdisciplinary forum. Membership is open to all members of the lunar exploration community and consists of lunar and planetary scientists, life scientists, engineers, technologists, human system specialists, mission designers, managers, policymakers, and other aerospace professionals from government, academia, and the commercial sector. LEAG reports represent consensus from the lunar exploration community. For the purposes of the Artemis III SDT, two LEAG study activities informed SDT deliberations.

The LEAG Lunar Exploration Roadmap (hereafter, LER) is a cohesive, community-developed strategic plan for lunar exploration, incorporating science priorities, commercial opportunities, and the relevance of a sustainable lunar surface presence for feeding forward to other destinations. The LER was initially released in 2012 and is a living document developed through a comprehensive community-based process, building most specifically from the results of the 2007 NASA Advisory Council Workshop on the Lunar Exploration Architecture (NAC, 2008). As a living document it is continually updated, most recently to account for feed-forward science at the Moon for small body research. The roadmap lays out a sustainable plan for Solar System exploration that allows NASA to use its lunar surface infrastructure to explore small bodies, Mars, and beyond. Of note for this SDT, the LER includes agreed-upon community prioritization and time-phasing designed to be used by policymakers and implementation actors to develop operational plans for engaging in lunar surface exploration and utilization activities.

The LEAG Advancing Science of the Moon report (hereafter, ASM-SAT Report) was commissioned by the Planetary Science Division of SMD in 2017 to assess progress made towards achieving the scientific goals of the 2007 SCEM Report. A large, diverse, multi-disciplinary team from the lunar exploration community deliberated over the course of three months to produce this written report. Although significant progress towards SCEM objectives had been made, surface exploration missions were clearly still needed to address most of the science goals highlighted in the 2007 SCEM Report. In addition, the ASM-SAT report highlighted three new focus areas where results produced since the 2007 report indicated further focused emphasis was warranted.

Finally, the SDT also considered the objectives and goals for lunar exploration as captured in the currently operative Planetary Decadal Survey, Visions and Voyages for Planetary Science in the Decade 2013-2022, as part of its deliberations. The definitive statement of planetary science priorities and the guiding document for all of Planetary Science, “Vision and Voyages” was produced during the 2009-2010 timeframe (during the Constellation program) and thus, its content is generally compatible with the expectation of an active lunar exploration program including human and robotic missions to the surface of the Moon. The Decadal survey was of particular use for outlining the value of lunar surface exploration for advancing all of Planetary Science.

Taken collectively, these documents provide a comprehensive assessment of priorities, established from extensive, broad-based community participation and relevant for any lunar exploration program. The Artemis III SDT was tasked with using these documents to establish the lunar exploration objectives that will be enabled by the Artemis III mission to the south polar region.

Additional community input (i.e., beyond the four guiding documents) was solicited and captured at multiple stages during the process of defining the science objectives for the Artemis III mission; details on the process can be found in Appendix 2. The SDT solicited white papers that focused on science objectives to be accomplished (rather than instrument or technology development recommendations); no limit was set to the number of white papers an individual or group could submit. A list of submitted white papers can be found in Appendix 4.

SECTION 4

ARTEMIS PROGRAM AND ARCHITECTURE SUMMARY

The first human expedition to the Moon in the 21st Century will provide exciting new opportunities for paradigm-advancing discoveries across a wide array of scientific disciplines.
Credit: NASA

4.0 Artemis Program and Architecture Summary

The Artemis program is a collective effort led by NASA to explore the Moon with a thorough, investigative approach combining science and human exploration objectives. Here, we describe NASA's plans as of this writing to provide context for the rest of this SDT report.

A coalition comprising NASA, international space agencies, and global space industry partners will establish an interconnected presence in lunar orbit and on the lunar surface (Figure 4.1). In orbit, the Gateway will provide a permanent command module for all lunar activities, facilitating transfer of crew and logistics supplies in support of surface missions as well as enabling unique science research and utilization demonstrations outside the protection of Earth's magnetosphere. On the surface, robotic landers will deliver science investigation payloads prior to a human mission to the south polar region in 2024.

Figure 4.1. As part of the Artemis program, NASA envisions a continuum of surface hardware and operations including astronaut extravehicular activities (EVAs), unpressurized and pressurized rovers, stationary habitats, and associated support systems such as power plants. Credit: NASA

Artemis will commence with robotic precursor missions deployed to lunar orbit and the lunar surface beginning in 2021 to return new information about the lunar environment and inform future science investigations and human mission planning. The Artemis I and Artemis II test flights of the deep space human transportation system—the Space Launch System (SLS) rocket, Orion crew vehicle, European Service Module, and supporting ground systems—will prepare NASA for the Artemis III mission, which will include the first human lunar landing of the 21st century in the south polar region of the Moon aboard the first use of the Human Landing System (HLS).

4.1 The South Polar Region

As described in the National Space Council's "A New Era for Space Exploration and Development", (National Space Council, 2020) the strategic emphasis of the Artemis program is to use the Moon as a proving ground for technologies and processes that will provide greater independence from Earth. As outlined in the "New Era" document, the intent is to achieve this through extraterrestrial operations, such as manufacturing and mining, as well as conducting cutting-edge lunar science, all of which will enable America and its international partners to mount historic human missions to other destinations and promote the creation of a thriving cislunar economy.

The selection of the Moon's south polar region (defined here as the area within 6° of latitude from the lunar south pole) as the location for the Artemis III landing site and the subsequent Artemis Base Camp reflects an emphasis on executing a sustained program of lunar exploration, with ample opportunities for commercial growth and international participation. This approach provides significant benefits, described below.

- Access to persistently illuminated areas of the Moon

The physiographic characteristics – slopes, crater density, and roughness – of the south polar region are not substantially different from other regions on the Moon. However, the very low Sun angles encountered in the polar regions have the effect of producing areas that are illuminated over most of a terrestrial year (Bussey et al., 2010; Mazarico et al., 2011; Speyerer et al., 2016; Glaeser et al., 2018). Areas have been identified on the lunar surface that are illuminated for over 200 days a year; such areas are few, but offer clear operational benefits (more favorable temperature regime, reduced duration of lunar nights, and persistent availability of solar power) that offer pathways to earlier, more capable missions and extended duration operations on the lunar surface.

- Potential access to surface-accessible volatile deposits that can be leveraged for large-scale resource utilization

The topography at the polar regions that produces areas of near permanent illumination also effectively blocks most of the sunlight at very low sun angles in some areas. These areas of constant or nearly-constant darkness in permanently shadowed regions (PSRs) can trap and collect various volatile species (Arnold, 1979, Bussey et al., 1999, Nozette et al., 1996, Li et al., 2018). The potential existence of accessible resources, such as hydrogen and oxygen, that can be straightforwardly leveraged represents an intriguing opportunity to "live off of the land" (e.g., Spudis, 2016). When the grade and tonnage of these volatile deposits are characterized, a cislunar economy could result, providing significant cost reductions for lunar surface logistics and resupply efforts (Spudis and Lavoie, 2011; Kutter and Sowers, 2016; Sowers and Dreyer, 2019; Cannon and Britt, 2020). Transporting hydrogen and oxygen harvested from the lunar poles to cislunar space would also be enabling for ambitious human expeditions to other destinations, as well as other activities throughout cislunar space.

These two clear operational benefits – persistent illumination and access to potential resources – led to the selection of the Moon's south polar region as the location of the Artemis III mission and the subsequent Artemis Base Camp. However, as outlined in this report, sustained lunar surface operations at the polar regions will enable a variety of exciting, paradigm-shifting science investigations. Local resource utilization enabled by the Artemis Base Camp will enable surface exploration architectures that ultimately enable future human expeditions to other high-value lunar destinations for scientific exploration. These destinations include irregular mare patches, lunar pyroclastic deposits, lunar “swirls,” evolved silicic volcanoes, and other geologic formations that are important for understanding the geologic history of the Moon and fully unlocking the Moon’s vast resource potential (Jawin et al., 2019).

4.2 Steady Innovative Progress

Through NASA’s Commercial Lunar Payload Services (CLPS) initiative, 14 U.S. companies are on contract and eligible to bid on science and technology payload deliveries to the Moon. Astrobotic and Intuitive Machines each have one task order award for deliveries in 2021. Astrobotic will carry 11 payloads to Lacus Mortis, a larger crater on the near side of the Moon, and Intuitive Machines will carry five payloads to the Aristarchus Plateau, a volcanic terrain in Oceanus Procellarum that is one of the Moon’s largest ore deposits (Hawke et al., 1990; Gaddis et al., 2003). Exploring the polar regions has been a high exploration priority for the past four decades (e.g., Taylor and Spudis, 1990; Nozette et al., 1996, 2001; National Research Council, 2007; NASA Advisory Council, 2008; Vision and Voyages, 2011; Lunar Exploration Analysis Group, 2016, 2017 a, b, c, 2018; Jawin et al., 2019; Li et al., 2018). To that end, Masten Space Systems has been awarded one task order to deliver and operate eight payloads – with nine science and technology instruments – to the lunar south polar region in 2022. In June 2020, NASA announced that Astrobotic would also deliver the agency’s Volatiles Investigating Polar Exploration Rover (VIPER) to the south polar region in 2023. VIPER and the Masten delivery will become the first surface explorers near the south pole of the Moon and will provide ground truth of the polar volatile deposits and the polar surface environment, furthering both scientific and exploration objectives. These early robotic investigations will increase our knowledge of the lunar environment and confirm the nature of the Moon’s vast resource potential, informing planning for future human and robotic expeditions, including Artemis missions beginning in 2024.

NASA’s SLS rocket, Orion crew vehicle, and supporting ground systems will be the backbone for deep space transportation. The first integrated flight test, Artemis I, will be an uncrewed flight to validate the systems’ performance in deep space and Orion’s thermal resilience to Earth-return speeds.

Artemis II will be a crewed test flight to validate the life support systems, communications systems and scenarios, and manual flight controls in a rendezvous and proximity operations demonstration.

Artemis III will be the first human mission to the Moon in the 21st Century. Astronauts aboard Orion for Artemis III will rendezvous with a Human Landing System (HLS) vehicle in lunar orbit to make their descent to the lunar South Pole. NASA has awarded three companies, Blue Origin, Dynetics, and SpaceX, to begin refining their HLS designs. Artemis III astronauts will spend up to 6.5 days on the surface, living inside the HLS crew cabin that they will then use to launch back to lunar orbit to rendezvous with Orion.

The Artemis III crew may rendezvous with the lander at the Gateway or may board the lander directly from Orion. While the SLS will launch crew aboard Orion, and potentially carry co-manifested payloads to lunar orbit, the increasingly capable commercial launch market will be the workhorse of lunar development. Commercial rockets are expected to carry CLPS landers and many other surface and orbital assets, including Gateway modules after Artemis III.

Science at the Moon will be enabled by crew access to the lunar surface. Pre-positioned assets are a potential consideration that could leverage CLPS delivery capabilities and relieve mass margins aboard the HLS. Pre-positioned assets could include geologic sampling tools, containers for sample return, instruments for geologic analyses, or experiments for crew deployment. Sample documentation equipment such as tags, barcodes, and cameras will also be necessary and can be pre-positioned.

During an extravehicular activity (EVA), the Artemis III astronauts will be confined to the exploration range dictated by their spacesuit capabilities. For Artemis IV and beyond, NASA plans to pre-position the lunar terrain vehicle (LTV)—an unpressurized rover—to expand the exploration range and allow a more diverse sampling of regional surface and subsurface specimens.

Artemis III is the first in a series of missions which is expected to culminate in the construction of the Artemis Base Camp, humanity's first permanent field station on another world, by the end of the 2020s (NASA Sustainability Plan, Space Council Document). The Artemis Base Camp will initially consist of a Foundational Surface Habitat (FSH), power systems, and mobility systems. As more surface infrastructure is added, future expeditions could last multiple lunar days or longer. For example, a pressurized rover would combine habitation and mobility, allowing astronauts to rove tens of kilometers from the lander in a shirt-sleeve environment, donning their spacesuits only for EVAs. Similarly, a surface habitat would extend the amount of time astronauts can live and work in a pressurized environment, donning their suits for moonwalks on foot, in the lunar terrain vehicle, or in the pressurized rover. The FSH is an essential component for enabling science activities on the lunar surface in the unique lunar environment. Together, these habitats enable exploration and experiments that require research facilities and long durations on the lunar surface.

4.3 Surface Operations and Moonwalks

The number of EVAs (or moonwalks) and their durations will depend on the down mass permitted on the HLS and the allocation of resources for the spacesuits and portable life support systems. NASA has established a minimum requirement of one planned and one contingency EVA for Artemis III, but the goal is for the crew to do at least four moonwalks with reserves available for a fifth contingency EVA. As the mission draws nearer and the landing site or region is defined, NASA will prioritize specific science activities for the surface expedition crew. While the specifics for the EVAs will be determined once the landing site is selected and a science plan is developed, we know that each EVA will begin with tool selection and preparation for investigations performed on that EVA.

4.4 Sample Acquisition and Curation

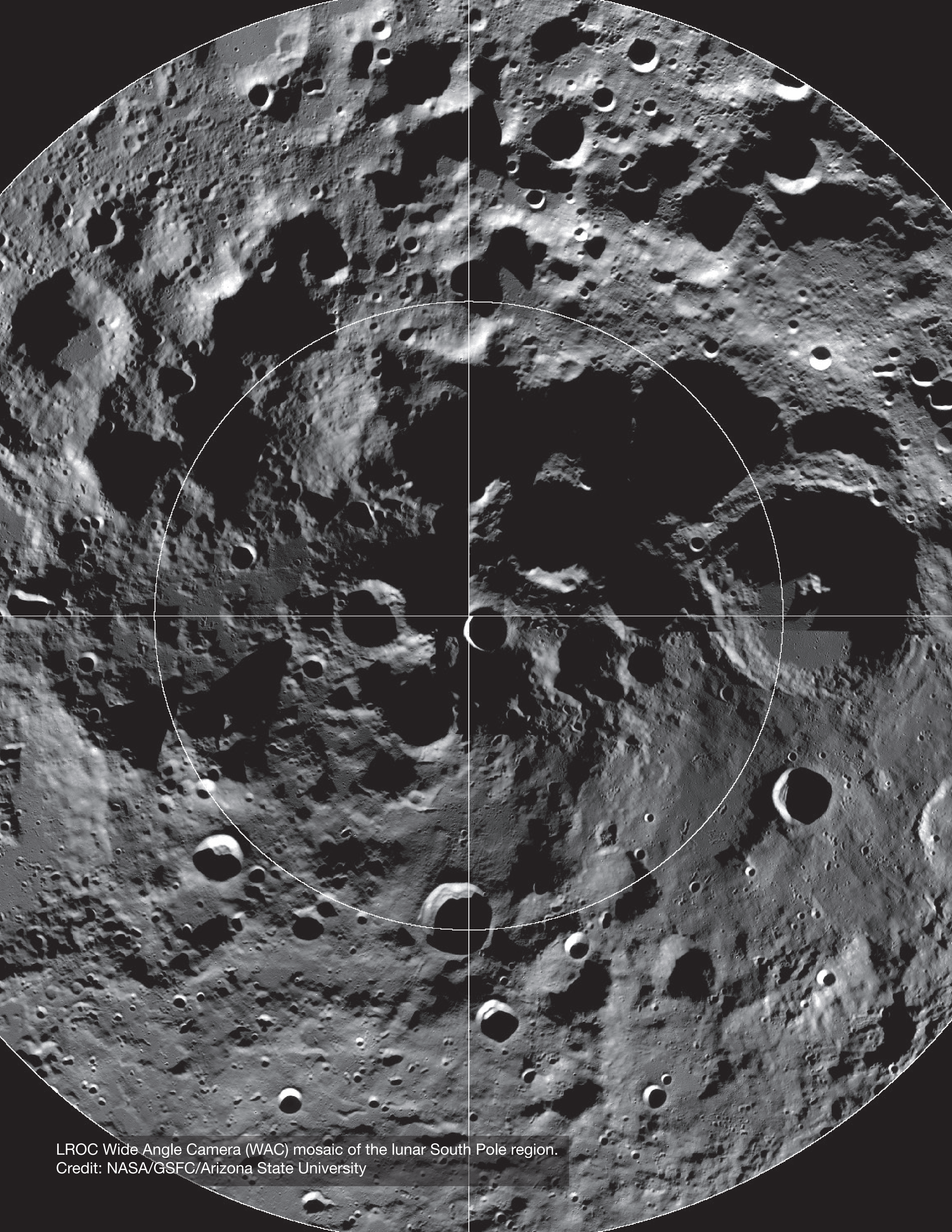
The Artemis acquisition and sample curation plan development is yet another multi-directorate effort to address sampling strategies, collection and curation tools, containers, storage, and transport from the lunar surface back to Earth. Because the lunar surface infrastructure is expected to grow throughout the 2020s, the plan includes a phased approach that begins with minimal assets assumed to be available for Artemis III, with gradually increasing capabilities based on additional assets throughout the decade. NASA may also have the opportunity to preposition geological sampling tools and storage containers using CLPS landers.

The goal of Artemis curation is to enable the sample science investigations needed to accomplish the Artemis science objectives, and to preserve the Artemis returned samples for future science to the greatest extent possible. To enable a robust program of sample acquisition and curation and provide seamless scientific access to Apollo and Artemis samples, extensive Artemis sample curation planning has already been started by the NASA Astromaterials Research and Exploration Science division at the NASA Johnson Space Center, which is the past, present, and future home of all NASA Astromaterials collections (Mitchell et al., 2020). Artemis sample curation requirements will be derived from the Objectives introduced in this report and refined as needed.

In addition, astronaut geology field training will evolve for the next cohort of astronauts to be specifically tailored to Artemis program needs to maximize the value of astronaut fieldwork in the unique lunar environment. In this training, astronauts learn many of the decision processes required for proper field science protocol and prioritization based on mass constraints for their ascent back to lunar orbit. They learn what types of samples to collect, how much of each, and how to properly document and store them for transport back to Earth (Eppler et al., 2016; Cohen et al., 2015).

SECTION 5

ARTEMIS SCIENCE OBJECTIVES AND TRACEABILITY TO SCIENCE PRIORITIES



LROC Wide Angle Camera (WAC) mosaic of the lunar South Pole region.
Credit: NASA/GSFC/Arizona State University

5.0 Artemis Science Objectives and Traceability to Science Priorities

The nomenclature the SDT has adopted in this exercise draws its overarching Objectives from the Artemis Science Plan (Section 2.1), populates each Objective with Goals drawn from the guiding community documents (Section 3), and identifies Investigations that describe specific activities that may be undertaken to address the Objective and Goal.

Seven overarching Artemis III Science Objectives were set out in the Artemis Science Plan (Section 2.1) and form the foundation of our traceability exercise. Expanded to encompass the full range of science goals identified in our Guiding Documents and submitted white papers, they are:

- Understanding planetary processes
- Understanding the character and origin of lunar polar volatiles
- Interpreting the impact history of the Earth-Moon system
- Revealing the record of the ancient sun and our astronomical environment
- Observing the universe and the local space environment from a unique location
- Conducting experimental science in the lunar environment
- Investigating and mitigating exploration risks

The Science Goals (areas of research) and Investigations (specific activities undertaken to address goals) mapped to these Objectives were used to populate a Science Traceability Matrix (Table 1). The Science Definition Team endeavored to include all Goals and Investigations that have been identified by the community over the last decade in previous reports and current white papers. The team's goal was to be as inclusive as possible in this effort, so that the scope of science that is of interest becomes clear to the reader, and so that future missions beyond Artemis III can build on the completed Investigations towards a more robust scientific understanding.

All of the identified Goals and Investigations represent important steps in making scientific progress. However, the Science Definition Team was charged with prioritizing activities based on its assessment of compelling science questions that can be reasonably executed during the Artemis III surface mission, and that build towards a more comprehensive program to be executed during future Artemis missions. The SDT undertook this prioritization at the science Investigation level. The team ranked each investigation using two independent criteria: compelling science (e.g., how fundamental is the investigation to making a significant advancement) and whether Artemis III presents an enabling opportunity (e.g., how feasibly can the investigation be performed during the Artemis III mission). In the prioritization, the team brought their scientific knowledge and expertise to bear but did not seek to re-evaluate every scientific Investigation. Rather, the team drew heavily on the community-submitted white papers, comments on the draft report, and previous community-developed documents and workshops. In many cases, prioritization is similar to the Lunar Exploration Roadmap, which in turn was derived from the Tempe workshop on science of the Moon enabled by Constellation (NASA Advisory Council, 2008). Because no significant US-led surface-based lunar activities have occurred since that workshop, many of the specific investigations have not been completed. In the years since that workshop, several areas of science have further matured or engendered renewed interest, including lunar tectonics, the origin of the Earth-Moon system, and the nature and origin of lunar volatiles. These science Investigations were prioritized relying on more recent documents such as the VVM-SAT and ASM-SAT. Though these documents and community contributions served as inputs to the process, the final judgement resided with the team.

Table 1 shows the full Science Traceability Matrix along with each Investigation's score on both criteria. The team then pulled the Investigations that scored highly across both criteria to develop further in the following sections, and to use as the drivers for building a potential program (Section 6). It is worth noting here that the program the team constructed based on this prioritization would potentially achieve much more than only these identified Investigations, because of natural synergies among activities such as sampling and field science. The Science Objectives and Goals are further discussed in the following sections, along with each of the highly ranked investigations.

5.1 Understanding Planetary Processes

One of the key motivations for studying the Moon is to better understand the origin and evolution of terrestrial planets in general, and that of Earth in particular. Although much of Earth's early structural evidence has been destroyed by active geologic processes (e.g., plate tectonics), the so-called "ancient" planets, including the Moon, retain more information about their early interior structure. The Moon was formed ~4.5 billion years ago, about 30-50 million years after the origin of the Solar System. The heat engine that drove differentiation of the Moon waned after the first ~1.5 Ga of lunar history as the volume of magmatism decreased dramatically. Therefore, the Moon represents an end member in terrestrial planet evolution as it potentially preserves the initial differentiation stage through a magma ocean. Complex internal processes drive the distribution of surface observables. Remotely sensed, geophysical, and sample data allow us to define several Goals and Investigations (summarized below) that test and refine models of planetary processes that have been established for lunar origin and evolution.

The Investigations outlined in this section can be achieved with a combination of sample analyses and deployed, long-lived geophysical instruments ("suitcase science"), the latter of which would make the first meaningful step towards a long-lived, globally distributed geophysical network that would fully realize the following Goals:

Goal 1a: Formation of the Earth-Moon system—The origin of the Moon is inextricably linked to that of Earth. Its formation affected the early thermal state of both bodies and therefore affected subsequent geologic evolution, and its presence continues to affect the rotation rate of the Earth, controlling the length of a day, and the tides. Although the consensus is that the Moon formed by the impact of a Mars-sized planetary embryo with the proto-Earth (Figure 5.1.1), the details of how the Moon accreted from the debris around the Earth or the chemical processes in the proto-lunar disk have not been worked out. Bulk lunar composition depends on (1) the composition of the impacting planetary body (and to a lesser extent the primitive Earth), (2) the extent of the fractionation of elements and their isotopes during formation of the Moon, (3) how completely or whether volatiles were lost, (4) whether the Moon could accrete with compositional heterogeneities, and (5) whether the Moon was essentially totally molten, before, during, and after accretion. Thus, determining the bulk composition of the Moon and the distribution of volatiles in the upper and lower mantle allows us to understand the conditions existing in the proto-lunar disk after the giant impact, and more generally to test whether that model is correct. Furthermore, documenting the diversity of crustal rock types and the structure and composition of both the shallow and deep lunar mantle will allow refinement of the lunar magma ocean hypothesis, the leading theory behind the formation of the lunar maria and highlands and the evolution of the Moon's crust and mantle. Not only does studying the origin of the Moon help us understand the early Earth, it also helps us to understand differences between Earth and the Moon and how conditions allowed life to evolve on the former.

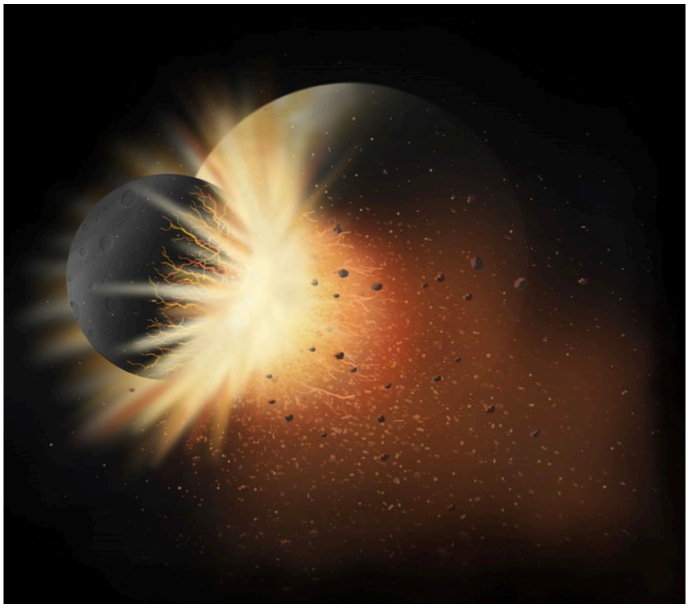


Figure 5.1.1: Moon-forming impact. The leading hypothesis for the origin of the Moon involves a huge collision between Earth and a planet half its size. That concept is often called the Giant Impact Hypothesis. This hypothesis suggests some of the colliding material was added to Earth, while a large fraction of the impact debris went into Earth orbit. The orbiting material then accreted together to form the Moon. The collision and subsequent accretion of the Moon occurred 4.5 billion years ago. Image credit: LPI.

Investigation 1a-1: Establish the mechanisms, timing, and extent of volatile depletion in the Moon—Material present and available in the early Solar System provided the building blocks of the Earth-Moon system. Work on the existing sample collection has demonstrated that primordial volatiles are present in lunar mantle source regions, which has implications for both the origin and evolution of the Moon's mantle. Water has been found in returned samples of pyroclastic glasses (Saal et al., 2008; Hauri et al., 2011) and crystalline mare basalts (e.g., Boyce et al., 2010; McCubbin et al., 2011). Evidence from remote sensing data also extends the detection of volatiles to unsampled lithologies such as KREEP-rich magmatic sources (Klima et al., 2013) and pyroclastic glasses (Milliken and Li, 2017). Estimates suggest that the abundance of volatiles released during the eruption of mare basalts may even have been sufficient to form a transient lunar atmosphere (Needham and Kring, 2017). To investigate further, we need samples from a site that is geologically and geochemically distinct from the Apollo landing sites, and hence likely to produce a different sample suite. Some polar landing sites are likely to contain clasts from both near and far side regions of the Moon. Relevant laboratory measurements on returned samples include abundances and isotopes of both highly volatile and moderately volatile elements, as well as geochronology to place volatile measurements in temporal context.

Investigation 1a-2: Constrain the physicochemical conditions and processes that operated at the surface of the lunar magma ocean—The formation of pure anorthosite rocks during differentiation on any planetary body is rare and has fueled ongoing debate about the origin and evolution of the lunar crust that range from being products of a global lunar magma ocean to formation as diapirs in serial magmatism, or a combination of both processes. In this investigation it is critical to collect a diverse sample set that represents lunar magma ocean products, such as Ferroan Anorthosite (FAN) and Magnesian Anorthosites (MAN) to establish differences and similarities to nearside FAN/MAN, for ground truthing, and for Lunar Magma Ocean (LMO) studies. Impact breccias should be included in this sample set as they might contain a wealth of rock fragments that originated from deeper within the crust and would give us insight into the lateral variation that operated in the magma ocean process. Precise age determinations, and detailed characterization of the samples, including detailed mineralogy, petrology, geochemistry, and isotopic investigations of these rocks, as well as volatile investigation require returning these samples for analyses in terrestrial laboratories and are critical to understand and constrain the physiochemical conditions and processes that operated at the surface of the lunar magma ocean in time and space.

Investigation 1a-3: Understand the size, chemical makeup, and timing of core formation— Recent work has put rough constraints on the structure of the core, which may include a solid inner core, a fluid outer core, and a partially molten layer (Williams et al., 2006; Garcia et al., 2011; Weber et al., 2011). These interpretations suggest the existence of these layers, but provide less explicit evidence for their depths, chemical composition, and density. The GRAIL lunar gravity mission produced a family of core models (Williams et al., 2014) all consistent with geodetic parameters (including constraints from lunar laser ranging; Williams & Boggs, 2015), but neither gravity data nor laser ranging have yet definitively identified the presence of an inner core. These parameters have fundamental importance for constraining the giant impact hypothesis and the Moon's subsequent evolution. It will help us to better estimate the bulk composition of the Moon, better understand the paleomagnetic record and the Moon's dynamo history, and overall to place constraints on global differentiation processes. This investigation involves geophysical measurements of the deep lunar interior (e.g. seismology, laser ranging, heat flow, electromagnetic investigations) that can be synthesized with the samples collected for other investigations (oriented samples are necessary) and orbital measurements such as remote sensing and radar. Surface gravimetry complements the primary geophysical measurements and may be considered if mass allocations permit (see Section 6).

Goal 1b. Planetary differentiation and evolution: formation of a magma ocean, crust, mantle, and core—During and immediately after accretion, the Moon underwent primary differentiation, hypothetically from an early global magma ocean (Figure 5.1.2). This involved the formation of a likely iron-rich core, a silicate mantle, and a relatively light, primordial crust. The initial bulk

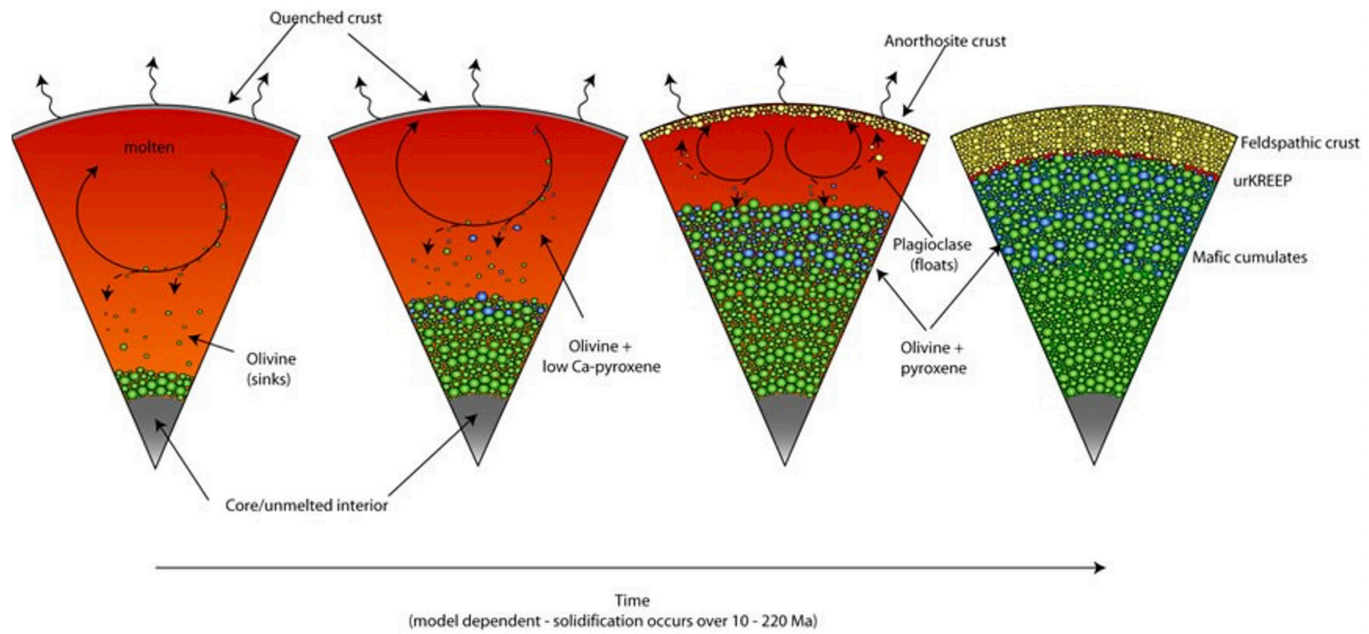


Figure 5.1.2: Lunar magma ocean crystallization. Shortly after accretion, a large proportion of the Moon was molten, referred to as the lunar magma ocean (LMO). Fractional crystallization of the LMO is currently the best model to account for known lunar lithologies and begins with crystallization of mafic cumulates of olivine and pyroxene crystals. Being denser than the melt, these cumulates sink into the interior to form the lunar mantle. After ~75 to 80 % of LMO crystallization, plagioclase begins to crystallize and being less dense, rises to the top of the LMO, producing a global anorthositic primary crust, now preserved in the lunar highlands. During the final stages of crystallization, dense ilmenite-rich cumulates form beneath the crust that are thought to later sink into the mantle, producing an overturn of mafic mantle cumulates. The residual late-stage melt is enriched in trace elements such as potassium (K), rare earth elements (REE), and phosphorus (P), referred to as KREEP. For more details, see Gross and Joy (2016).
Image credit: LPI/CLSE/Jennifer Rapp

composition, as well as the pressure and temperature conditions during this separation, are reflected in the Moon's current chemistry, structure, and dynamics.

Although there are some constraints on the composition of the outermost layers of the Moon's crust, that of the bulk crust is less well known. Although our improved knowledge of lunar gravity and the internal structure of the Moon from the NASA GRAIL mission resulted in significant progress in our understanding of the lateral variability of the thickness of the lunar crust on regional and global scales, GRAIL data are constrained by uncertain single-point Apollo seismic estimates. The bulk composition of the mantle is similarly under-constrained, and the presence of compositional and structural stratification, bearing on the late stages of differentiation and the efficiency of subsequent convective mixing, cannot be confirmed or refuted. For example, a putative 500-km seismic discontinuity has been interpreted as indicative of chemical stratification in the mantle and possibly the base of the lunar magma ocean (Wieczorek and Phillips, 2000).

Understanding the character of the lunar core and whether a global dynamo was present is essential for developing accurate models for the Moon's formation. The average density of the core could imply either a large concentration of lighter alloying elements or a high core temperature (Garcia et al., 2011). The existence of a partially molten layer suggested in Weber et al. (2011) was further examined with lunar geophysical data in combination with phase-equilibrium computations and with a viscoelastic dissipation model (Khan et al., 2014; Nimmo et al. 2012); these studies yielded conflicting results. Laser ranging data suggest the lunar core is liquid (e.g., Williams et al., 2006; Williams and Boggs, 2015; Barkin et al., 2014), although combining gravity, topography and laser ranging data to model the deep interior of the Moon (Matsuyama et al., 2016) produced a solid inner core and total core size akin to the core modeled using Apollo seismic data (Weber et al., 2011).

Investigation 1b-1: Determine the extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation—Understanding and relating the different and asymmetrically distributed geochemical terranes on the Moon, such as pure anorthosites, KREEP, and farside magnesian feldspathic highlands, to lunar formation and differentiation remains a fundamental goal of lunar sciences. This investigation involves synthesizing local and regional remote sensing and sample data to inventory and map the different rock types present at the site, determine the sequence and structure within the lunar interior, and reconstruct lunar differentiation in space and time. Using remote sensing as a guide to find these terrains (i.e., magnesian anorthosites, KREEP-bearing layers, pure anorthosite, potential mantle material, etc.), it is critical to collect a diverse set of samples that represent the complex geology of the site. Precise age determinations, and detailed characterization of the samples, including detailed mineralogy, petrology, geochemistry, and isotopic investigations of these rocks, require returning these samples for analyses in terrestrial laboratories. These data are critical to compare to ground truth orbital data, to put into context our lunar meteorite collections, and for our understanding of initial lunar differentiation and the initial differentiation of other planetary bodies.

Investigation 1b-2: Determine the bulk composition of the crust and mantle—The bulk composition of the crust is an important component of the total lunar composition, particularly in assessing the abundance of elements concentrated in it (incompatible lithophile elements, e.g., rare earth elements). Sample, geophysical, and remote sensing data indicate that the crust is highly variable in composition, which indicates that the lunar mantle is likely to reflect this variability. This in turn reflects the combination of primary differentiation and subsequent dynamics, including convection, partial melting, and magma migration and emplacement. Investigating the bulk composition of both the lunar crust and mantle through sampling (derived from a variety of depths within the Moon), the deployment of geophysical payloads designing to probe the subsurface (in particular, determining crustal vs. mantle heat flow), and comparing these point data to remotely sensed global datasets will give us a broader picture of the crustal compositional structure, layering, and heterogeneity as well as the corresponding heterogeneity and volatile composition of the lunar mantle. *In situ* measurements through geophysical payload deployment, as well as sample return, are valuable, as Artemis III measurements will be the first step in a larger understanding of these processes on a global scale.

Investigation 1b-3: Inventory, relationships, and ages of nonmare rocks—Rocks in the lunar crust shed light on the processes that operated in the lunar magma ocean, the range of magma compositions subsequent to primary differentiation, the chemical and mineralogical composition of their mantle source region, and ultimately planetary differentiation. This investigation involves collecting and inventorying a diverse sample set of nonmare rock types at the lunar surface that represent the complexity of the site. These should include samples from the primary crust such as FAN, MAN, troctolitic suite, etc. to sample the crust broadly and to determine lateral or regional variations, as well as samples from crater and basin ejecta to access varying depth levels. Precise age determinations, as well as detailed mineralogy, petrology, and geochemistry of these rocks, require returning these samples for analyses in terrestrial laboratories. This investigation can be coupled with remote sensing and geophysical measurements to determine the sequence and structure within the crust and to reconstruct crustal evolution in space and time.

Goal 1c: Volcanism: partial melting, eruptions, flow sequence and compositions—Following differentiation of the lunar magma ocean, the Moon transitioned to magma production by a series of magmatic events probably driven by convection and partial melting in the mantle. The physical volcanology of the Moon includes study of extensive, relatively thin mare basalt lavas and pyroclastic deposits. The iron- and titanium-rich lunar pyroclastic deposits, found at the Apollo sites, resulted from fire fountain or explosive eruptions from volatile-rich basaltic magmas ascending from deep mantle sources and erupting as a spray of magma, often forming tiny glass or crystalline beads. The volatile phase included magmatic volatiles (i.e., F, Cl, S, and Zn, left behind on the surfaces and interiors of pyroclastic beads) and also water vapor, which has been discovered trapped in lunar pyroclastic glass beads. Such metals, hydrogen, and oxygen are regarded as potentially valuable lunar resource materials. This work sheds light on lava flow emplacement mechanisms, eruption mechanisms and fluxes, the rate of magma production in the mantle, and the variation of these processes through time, as well as magma migration mechanisms and the thermal history of the mantle. The concentration and composition of volatiles associated with volcanic eruptions of both lava flows and pyroclastic deposits also bear on models for planetary accretion and lunar origin.

Goal 1d: Tectonism: deformation of the crust and thermal history—In the past decade, greatly expanded high-resolution image coverage of the lunar surface has led to explosive growth in the number and quality of observations of tectonic landforms on the Moon (e.g., Watters et al., 2010, 2012; Banks et al., 2012; Williams et al., 2013, 2019). Although it was once thought that most tectonic structures are located on the near side, spatially associated with mare basins, recent studies have indicated that lobate scarp faults are globally distributed (Watters et al., 2015, 2019). Wrinkle ridges are located within mare basins, whereas lobate scarps and graben are found in both mare and highlands regions (Watters et al., 2015, 2019; Nahm et al., 2018). As surface expressions of thrust faults, lobate scarps require crustal contraction to form and develop through subsequent fault slip. These structures are thought to have formed in part as a response to compressional stress resulting from late-stage global cooling, and may still be active at the present day (Watters et al., 2019), which would have important implications for both future scientific and human exploration of the Moon. In the absence of plate tectonics, the number and distribution of faults, as well as their seismic activity, are important factors to consider when investigating planetary formation and evolution, and also have safety implications for infrastructure supporting a sustained human presence at the lunar south pole. The interior structure, thermal history, and mechanism(s) of heat loss of a planet are all related to the resulting distribution of surface tectonic features.

Goal 1e: Impact processes: basins and craters, mixing of the crust, crustal stratigraphy— Impact cratering is a fundamental process that affects all rocky planetary bodies. The Moon is a valuable, easily accessible, and unique testbed for studying all phases of the impact process, from initial contact to final modification and adjustment. Open questions remain about impact cratering at all scales that would benefit from future lunar exploration. For example, it is not fully understood: (1) how ejecta from basins and craters are distributed and vary with distance from the structure, (2) how the ballistic sedimentation process works, (3) the extent of impact-induced vertical mixing, (4) how megaregolith forms and affects the bulk composition of the lunar crust, or (5) how impact facies and compositions can be used to deduce crustal stratigraphy. The intense bombardment of the lunar highlands crust where Artemis III will land has left little bedrock intact. Thus, to interpret the present surface, it is essential to understand how cratering mixed and deformed the original crustal rocks and obscured the original distribution of the products of primary differentiation and subsequent geologic activity.

Goal 1f: Regolith processes and weathering—The Moon is a natural laboratory for regolith processes and weathering on anhydrous bodies. Regolith, exemplified by the lunar regolith, forms on airless bodies of sufficient size and retains a significant fraction of the ejecta from impact events. The regolith has accumulated representative rocks from both local and distant sources since the most recent resurfacing event (e.g., the deposition of lavas or a substantial impact debris layer). It also contains addition, modification, and alteration products introduced and induced by meteoroid and micrometeoroid impacts, and modifications due to the implantation of solar and interstellar charged particles, radiation damage, spallation, exposure to ultraviolet radiation, and so on (e.g. space weather; Figure 5.1.3). Knowledge of the processes that create, modify, and transport

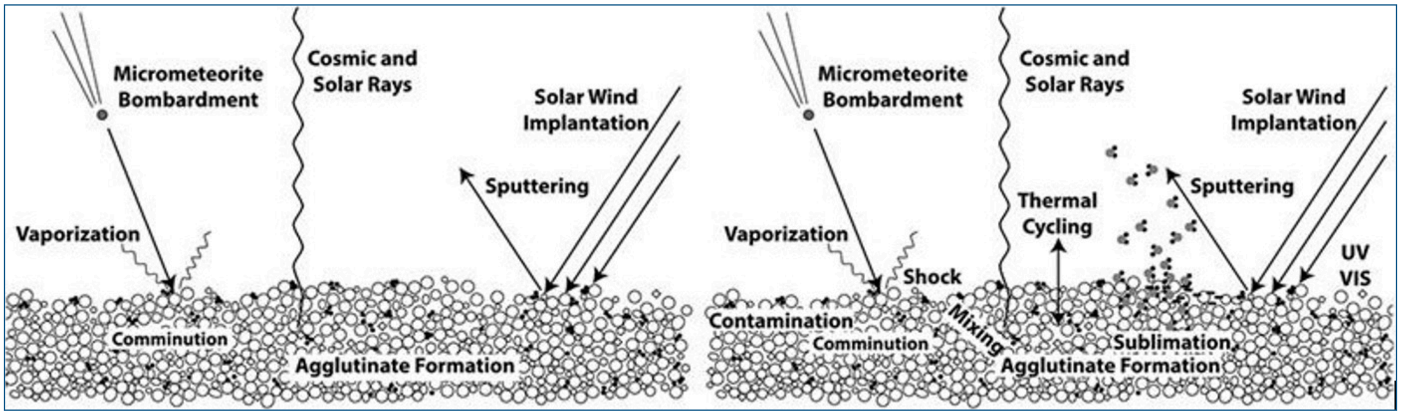


Figure 5.1.3: The complex array of processes involved in space weathering of airless bodies. Typical soils are particulate but heterogeneous in composition. (left) Dominant processes affecting the surface of the Moon at 1 AU (after Noble, 2004). (right) The broad range of surfaces processes now believed to be active across the solar system but with different degrees of prominence for specific environments. *Reproduced from Pieters & Noble (2016)*

the lunar regolith is essential to understanding the compositional and structural attributes of other airless planet and asteroid regoliths.

Investigation 1f-1: Determine physical properties of regolith at diverse locations of expected human activity—Owing to the importance of regolith to the exploration of the lunar surface and for lunar resources, developing a thorough understanding of regolith properties (including chemistry, mineralogy, physical and geotechnical properties, volatile content and storage mechanisms, and regolith formation) is critical to taking advantage of this vital resource. Obtaining samples, especially drill cores, from a diversity of locations where human exploration is possible (especially in the polar regions where there are no analyses so far) is important for future program success. Visiting a greater diversity of locations, taking deep core samples, and completing borehole analyses are all critical to obtaining a more complete understanding of the lunar regolith. Geophysical profiling of the regolith in and around the Artemis III landing site will be important for mapping rock abundance with depth as well as identifying different regolith/megaregolith horizons.

5.2 Understanding the Character and Origin of Lunar Polar Volatiles

Lunar volatiles are of high priority for both science and exploration. The lunar polar cold traps provide an unprecedented record of Solar System volatiles delivered from numerous sources (comets, asteroids, solar wind interactions, interior outgassing, etc.) over an extended period of time. This cumulative treasure is also key to understanding the behavior and history of volatiles on our Moon as well as other airless bodies in the Solar System.

Scientifically, we seek to first characterize the distribution and form of both surface and subsurface volatile concentrations. Such knowledge, coupled with an understanding of geologic context gleaned from *in situ* observations and measurements by the astronauts as well as remotely acquired data and analysis of returned lunar samples, will allow assessment of the distribution and character of volatiles in other lunar polar regions. In addition to characterizing the location and form of volatiles, understanding the sources, sinks, and transport of volatiles at the Moon is also of high scientific priority. This information can provide valuable constraints on the formation and evolution of lunar volatile deposits as well as bound similar processes on other airless bodies. In terms of long-term exploration priorities, water ice in particular may be a valuable reserve for ISRU (*in situ* resource utilization) to enable a sustained human presence on the Moon. The lunar poles present unique environments where volatile deposits can be cold trapped and sequestered on the surface and subsurface. The Artemis III mission thus provides a prime opportunity to make significant advances in our understanding of these special and accessible Solar System volatiles.

Water ice and other volatiles have been theorized for several decades to exist in extremely cold permanently shadowed craters near the poles. Several forms of evidence from remote sensing measurements have suggested the presence of volatiles near the poles. For example, data from the Lunar Prospector neutron spectrometer clearly indicated enhanced polar hydrogen (Feldman et al. 1998), and anomalous radar returns from the Clementine (Nozette et al. 1996), Chandrayaan-1 (Spudis et al. 2010), and the Lunar Reconnaissance Orbiter (LRO) (Patterson et al. 2017) missions are consistent with ice. The LRO LEND (Lunar Exploration Neutron Detector) data also showed enhanced polar hydrogen (e.g., Mitrofanov et al. 2010; Sanin et al. 2017; Figure 5.2.1), while the LRO LAMP (Lyman Alpha Mapping Project) measured UV albedo consistent with surface water ice in some cold traps (Hayne et al. 2015; Figure 5.2.2). In addition to these measurements, predictive stability maps for water and other volatiles have been produced using LRO data from the Diviner

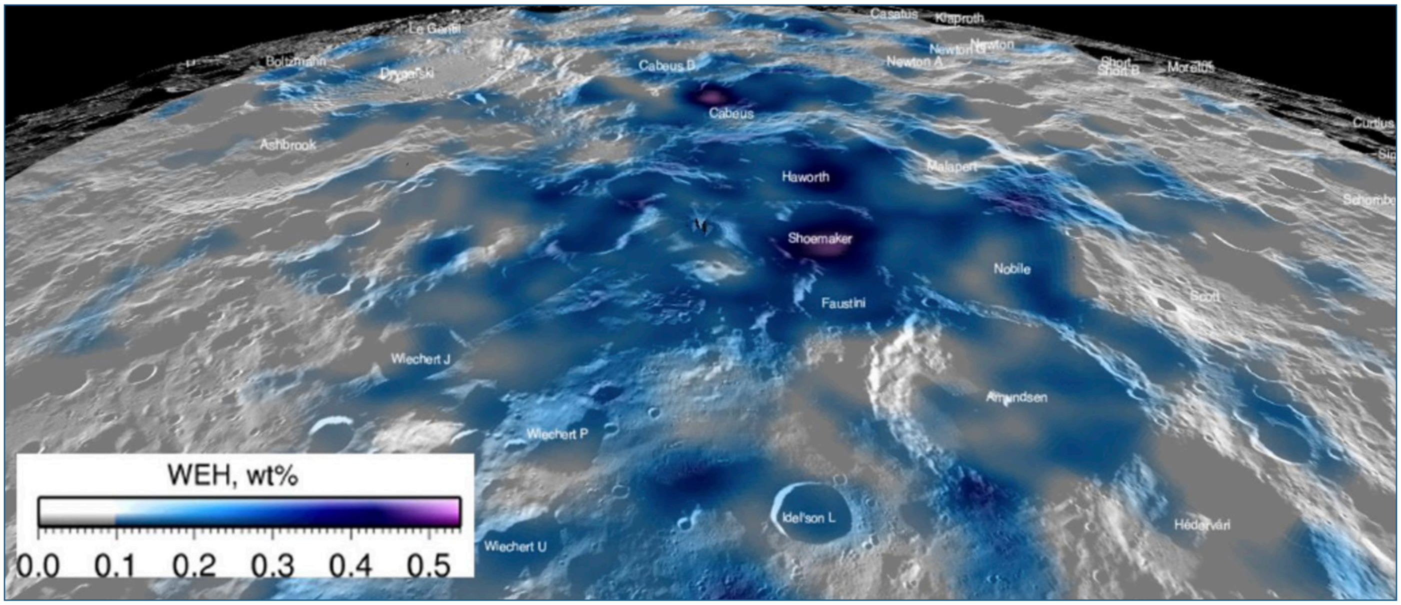


Figure 5.2.1: LEND polar water equivalent hydrogen WEH map. Perspective view of the estimated abundance of water equivalent hydrogen around the lunar south pole. Map from Sanin et al. (2017) and overlain on LROC WAC mosaic in Lunar QuickMap (https://bit.ly/2T46NdO).

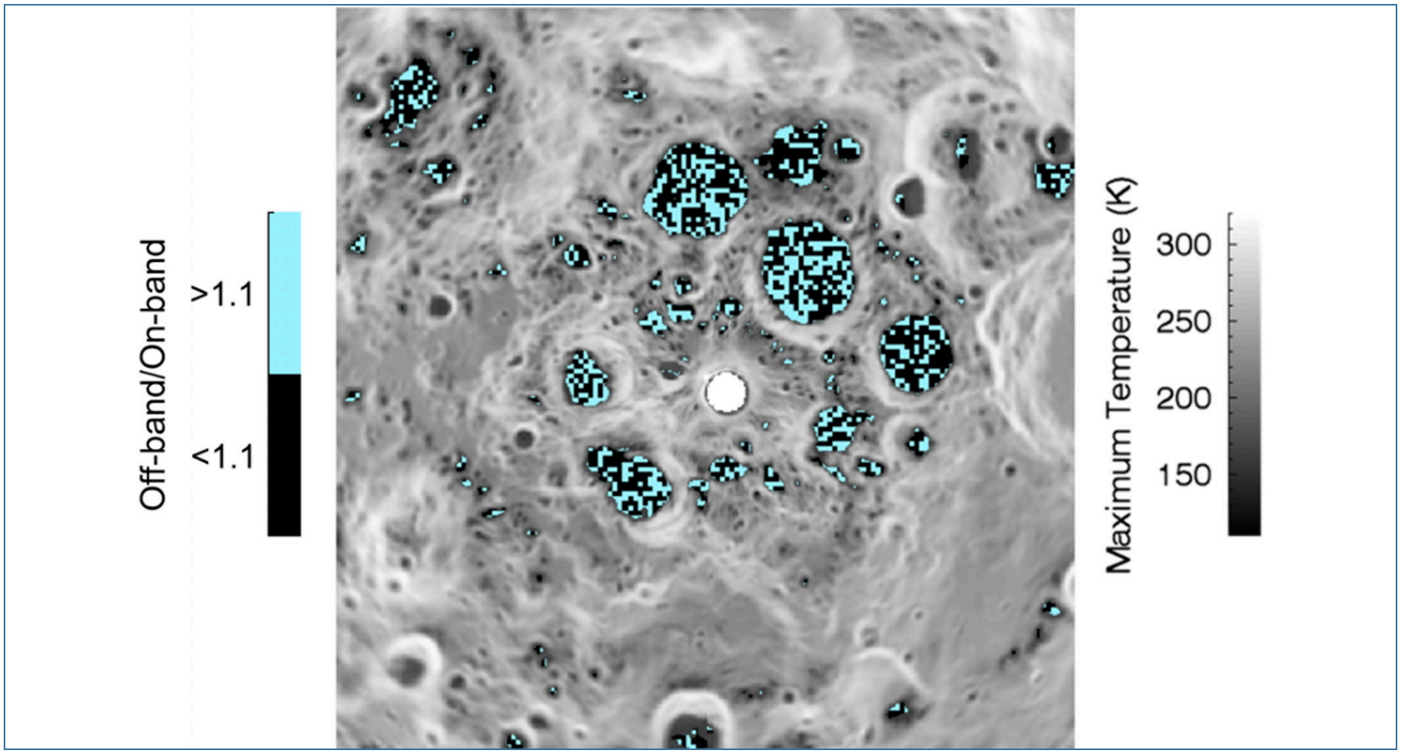


Figure 5.2.2: LRO LAMP surface water ice map. Location of anomalous LRO LAMP UV albedo measurements consistent with water ice. Off/on albedo ratios of >1.1 are consistent with surface water ice located within cold traps where cold traps are defined as regions below a stability temperature threshold of ~110 K. The interior of Shackleton Crater is not evaluated due to contamination of the LAMP data by reflected sunlight. Magana et al. 2020 (in prep).

thermal radiometer, and these thermal data suggest subsurface volatiles may also be stable in areas of temporary sunlight near the poles due to low subsurface temperatures which could enable sequestration of volatiles (Paige et al. 2010; Figure 5.2.3).

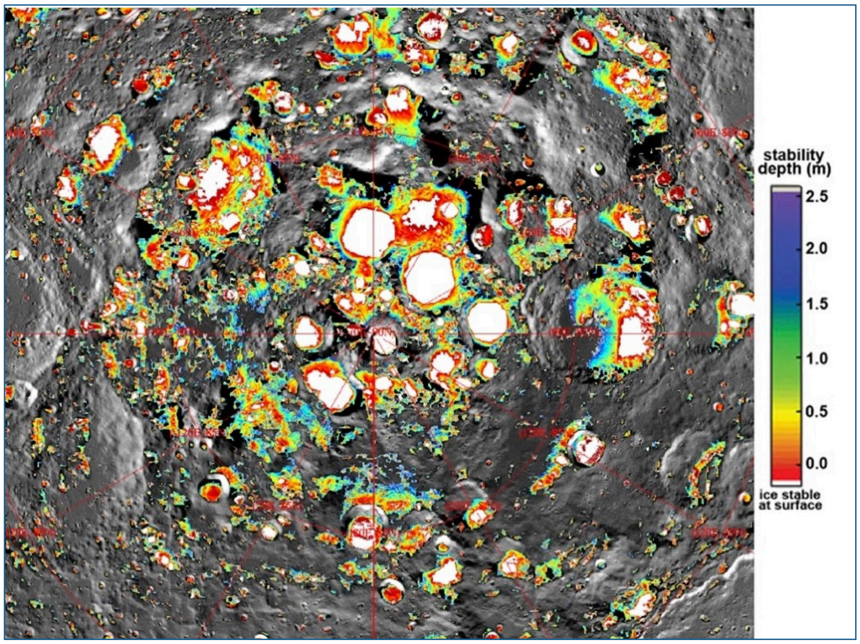


Figure 5.2.3: LRO Diviner current model polar ice stability map. Model-calculated depths at which water ice would be lost to sublimation at a rate of less than 1 kg m^{-2} per billion years (Paige et al. 2010). The white regions define the locations where water ice can currently be cold-trapped on the surface, the colored regions define the upper surface of the lunar ice permafrost boundary, and the gray regions define locations where subsurface temperatures are too warm to permit the cold-trapping of water ice within 1 m of the surface. Map from Lunar QuickMap (https://bit.ly/368SNpq).

In 2009, LCROSS (Lunar CRater Observation and Sensing Satellite) impacted a permanently shadowed areas of the Cabeus crater in the south polar region and detected water ice and a variety of other volatile components (Colaprete et al. 2010). In addition to such polar-focused analyses, the M3 (Moon Mineralogy Mapper) aboard the Chandryaan-1 spacecraft (Pieters et al. 2009), Cassini Visible and Infrared Mapping Spectrometer (VIMS) (Clark 2009), and Deep Impact (Sunshine et al. 2009) spacecraft all detected global OH or H_2O at the cooler high latitude regions and lesser amounts at lower latitudes across the Moon. Recently, statistical analysis of low M3 signal at the poles enabled small amounts of water ice to be directly detected in the shadowed regions (Li et al. 2018).

Our understanding of lunar polar volatiles has been significantly improved over the past decade through such new data and analysis. However, the spatial resolution and/or precision of these datasets is low, and major unknowns remain about the abundance, composition, distribution, and origin of lunar volatiles at the poles (Figure 5.2.4). These important outstanding questions can be effectively addressed through coupled *in situ* measurements, sample return, and long-lived deployable instrument packages in the lunar polar region.

The goals described here focus on the highest priority science that could be realistically addressed during the Artemis III mission. The highest priority objectives include detecting, characterizing, and mapping the geographic distribution of volatiles in the polar region and determining their physical state and abundance. For ice, as discussed by Colaprete et al. (2020), four polar ice stability regions (ISRs) are currently envisioned locally and regionally: Surficial (ice expected to be stable at the surface), Shallow (ice expected to be stable within 50 cm of the surface), Deep (ice expected to be stable within 50-100 cm depth), and Dry (temperatures within the top 1 m expected to be too warm for ice to be stable) regions. Astronauts could progressively perform *in situ* measurements, collect samples, and/or deploy instrument packages, as applicable, sequentially from

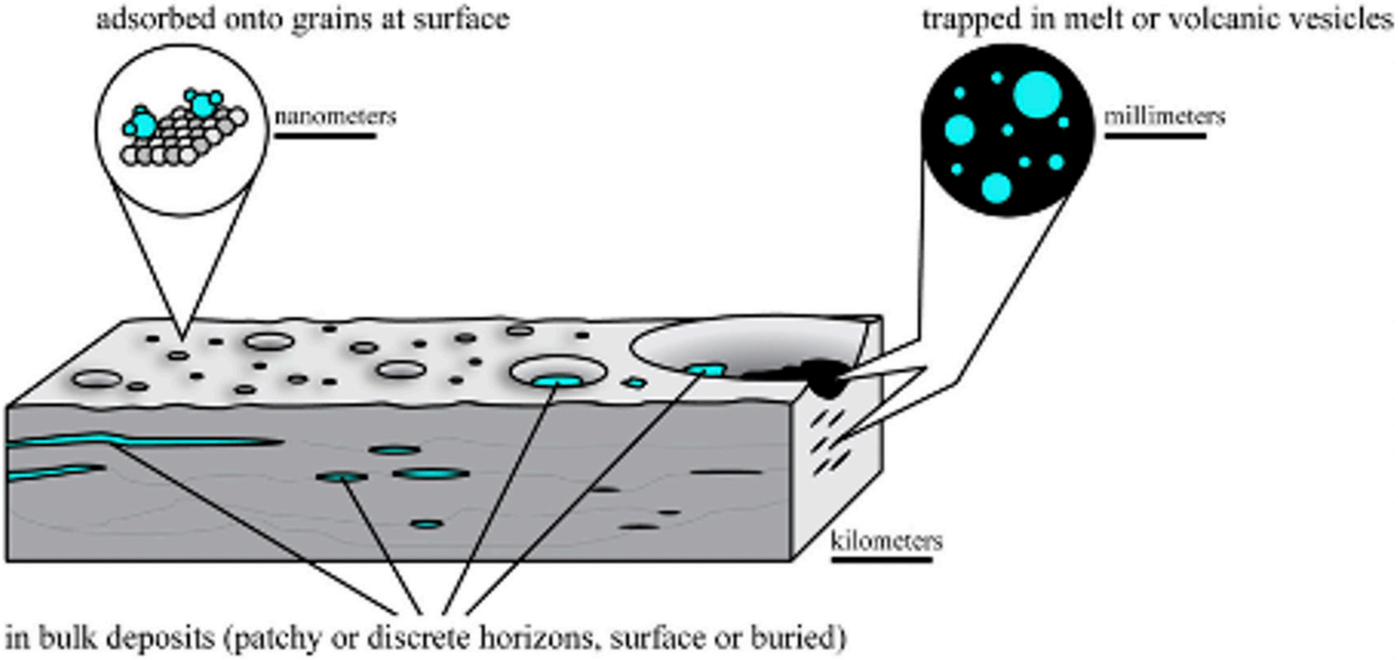


Figure 5.2.4: Possible forms and scales of lunar polar volatile deposits. A schematic diagram illustrating the potential distribution and scale of volatile components across the surface and trapped near or below the surface at the lunar poles (e.g., adsorbed molecules, grains with altered or trapped hydrated minerals, surface frost, buried deposits). Credit: LPI/CLSE.

the Dry (warmest and most sunlit) region followed by the Deep, Shallow, and then Surficial (i.e., within a PSR) ice stability regions. This represents an order of increasing operational complexity due to the corresponding environmental conditions (thermal and lighting). Long-lived instrument packages are utilized where science objectives require measurements to be collected over timescales longer than the expected surface stays of Artemis III astronauts on the lunar surface. In all cases where samples are collected for return to Earth, careful *in situ* characterization of these samples is also required due to current uncertainties in requirements for volatile sample collection, transport, storage, and analysis.

Goal 2a: Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and with depth) of the volatile component in lunar polar regions— Despite advances in our understanding regarding the composition and distribution of volatiles in the lunar polar regions, our understanding remains incomplete. Significant advances can be made on the Artemis III mission to characterize lunar polar volatile deposits through targeted investigations. For example, investigations include identification of surface frost composition by detecting water ice and other species, if present, and establish a lower limit on abundances. This can be accomplished through examining micro PSRs, transiently shadowed regions, and/or PSRs. Surface frost locations should also be assessed and mapped locally on order of 10 to 100s of m over kms, and regionally with greater mobility at ~ 1 km spacing over scales of 100s of km. Identifying speciation of surface hydrogen in the local region is important as well as determining the abundance of hydrated species with depth across ice-stability zones from 0 cm (surface) to 100 cm (deep). Similarly, measuring the distribution of surface and subsurface hydrogen laterally across scales of 1 m to at least 1000 m in polar regions is important for extending Artemis III data to remotely acquired datasets. Ground truth *in situ* measurements tied to samples collected are key tie points to enable the use of remote sensing hydrogen maps to accurately assess the surface and subsurface hydrogen species and distributions. Micro cold traps may also play a significant role in the modern sequestration of volatiles and thus the distribution of micro cold traps must be assessed across the lunar surface within dominantly illuminated regions.

Investigation 2a-1: Identification of surface frost composition—Current ultraviolet and near-infrared spectral data along with temperature measurements combine to indicate the presence of discontinuous surface water ice frosts in the polar regions of the Moon (e.g., Hayne et al. 2015). Confirmation of water ice as well as detection of additional volatile components within exposed frosts can be accomplished during the Artemis III mission with surface measurements and sample collection in regions accessible by humans. Regions to be examined include PSRs, micro PSRs, and transiently shadowed regions. Required measurements include spectral identification of volatiles and their relative abundances (e.g., H_2O, CO_2, CH_4, H_2S, NH_3, SO_2) and analysis of isotopic ratios such as deuterium to hydrogen ratio (D/H). *In situ* surface measurements and sample return are required.

Investigation 2a-2: Identification of surface frost locations in spatial context—Local surveys of frost environments are important for understanding the controlling environmental variables regarding frost deposition and retention. PSRs, micro PSRs, and transiently shadowed regions outside of the disturbed landing zone should be surveyed. Increased mobility is better for increased coverage and assessment, but with appropriate tools astronaut walking distance is likely sufficient for initial identifications of surface frost locations. Larger scale regional surveys of surface frost utilizing *in situ* measurements, but without a rover capable of traversing distances on the km-scale will be difficult. If *in situ* tools are optimized for frost assessment, only surface measurements are required and thus no subsurface access is needed for this Investigation. *In situ* surface measurements coupled with surface sample return is required.

Investigation 2a-3: Temporal variability of frost—Although not all the variables affecting the presence or absence of surface frost are known, it is clear the average and diurnal temperature of the surface is key. Temperatures affecting the stability and presence of frost on the lunar surface are expected to vary over diurnal and seasonal timescales. Monitoring the temporal variation of surface frost will require longer term measurements than afforded by the Artemis III EVA durations. Frost surveys conducted by the astronauts would benefit from landing in the early morning to assess time of day changes in frost deposition and location. Such initial measurements can be made *in situ* by astronauts and through targeted sample collection. The deployment of longer-term instrument packages is required for time-dependent measurements over a minimum of one lunar day/night cycle.

Investigation 2a-4: Speciation of surface hydrogen—Data from the Lunar Prospector and LRO missions have indicated areas of enhanced hydrogen in the lunar polar regions. However, these datasets cannot determine the form of this hydrogen, which may contain multiple H-bearing compounds, each with different origin and stability constraints. Measurement of the speciation of surface hydrogen can be made from different locations in the vicinity of the Artemis III lander outside of the landing (contamination) zone. Evaluation of the diversity of hydrated species is also important to better utilize remote sensing observations and as constraints for space weather processes on surface materials at the poles. Measurements are preferred in both sunlight and shadow. Coordinated *in situ* surface measurements and surface sample collection is required.

Investigation 2a-5: Understand surface hydrogen speciation spatial variability—The lunar polar hydrogen observed with remote sensing data indicates significant spatial variability across the lunar surface, although obtained at low spatial resolution. Measurements of surface hydrogen across spatial scales over 1 km or more are desired to characterize the lateral variation of hydrogen and its associated abundance and speciation. Measurements are dependent on local geology and are preferred in both sunlight and shadow. *In situ* surface measurements and surface sample collection is required.

Investigation 2a-6: Spatial distribution of subsurface hydrogen—Data from the Lunar Prospector and LRO missions have been used to model areas of enhanced subsurface hydrogen in the lunar polar regions. The low spatial (lateral) resolution of these datasets coupled with uncertainties in hydrogen depth distributions and the inability to determine the form of the hydrogen from these measurements requires direct characterization of the hydrogen in both lateral and vertical dimensions on the Moon. Measurements both within and outside of PSRs and in varying ice stability regions (dry, deep, shallow, surface) to assess subsurface spatial variations are required to adequately characterize the hydrogen deposits. Measurements to ~1 m depth are necessary in order to validate and extend existing hydrogen data obtained remotely. Characterizing the lateral H variability requires multiple measurements across the lunar surface and hence mobility. The assumed initial mobility afforded by Artemis III is reasonable to achieve these goals (to ~1000 m distances). Subsurface samples (cores and/or discrete samples collected at varying depths up to 1 m) collected without significant de-volatilization coupled with *in situ* measurements are required.

Investigation 2a-7: Determine distribution of micro cold traps across lunar surface within illuminated regions—Micro cold traps may represent a significant reservoir of lunar polar volatiles and offer important clues regarding volatile behavior near the lunar surface. The size of such micro cold traps must be constrained as water (and/or other volatiles) can exist only where burial and destruction rates are outweighed by volatile delivery rates (which are currently unknown). These regions can be identified via tools to measure precise surface thermal measurements for cold trap mapping, and complementary spectral measurements to confirm volatile composition(s). These measurements can be accomplished on the Artemis III mission with *in situ* measurements and mapping within sunlit areas. Sample return is also desired, although depending on size(s) and accessibility of the identified micro cold traps, sample collection of volatiles with minimal volatile loss could be challenging.

Goal 2b: Determine the source(s) for lunar polar volatile deposits—The origin of the polar volatiles is currently unknown but with contributions expected from multiple sources such as comets, asteroids, solar wind interactions, and/or interior outgassing. Understanding these source(s) will provide valuable insight into the billion year history of volatile transport and retention.

Investigation 2b-1: Origin of the polar volatiles—This Investigation can be accomplished with measurements from PSRs and transiently lit areas where near subsurface temperatures have allowed for an accumulation of volatiles. Characterizing the concentration, chemistry, and temperature of volatiles is important for informing the origin of the volatiles. In addition, measuring stable isotopic ratios (e.g., D/H, ${}_{18}O/{}_{16}O$, C, N, S, etc.) can distinguish between solar wind, cometary, and endogenic end members, and place constraints on the relative contributions of each potential source. *In situ* measurements coupled with sample collection (including surface samples and subsurface core samples) with minimal volatilization are required.

Goal 2c: Understand the transport, retention, alteration, and loss processes that operate on volatile materials near and at permanently shaded lunar regions—The subsurface stratigraphy of volatile deposits harbors clues pertaining to the history of volatile sequestration and loss within the polar regions. By determining variations in the composition and physical properties with stratigraphy of the regolith to a depth of 1 m at several sites, we will systematically characterize the locations and characteristics of subsurface volatiles. By assessing the distribution of water/OH laterally and vertically within a PSR we will characterize the spatial distribution of these volatiles and also begin to link this information with the remotely acquired hydrogen maps to develop constraints on the transport, retention, alteration, and loss of volatiles. *In situ* ground truth thermal measurements are also important to refine and/or validate thermal models which predict ice stability regions and thus the horizontal and vertical distribution of volatiles. Following these *in situ* characterizations, the temporal variability of surface frosts and volatile components can be monitored by deploying long-lived instrument packages on the Moon.

Investigation 2c-1: Distribution of water/OH within a PSR—Addressing this Investigation requires a lateral assessment of water/OH with a PSR coupled with vertical documentation of 0.5% water-equivalent H (+- 50%). Obtaining samples at intervals of 10-20 cm to a depth of 1 m or more are necessary. These measurements require subsurface access without significant de-volatilization and will necessitate *in situ* surface measurements as well as sample collection. The timing of measurements and sample collection is also critical to document since the local thermal environment, even in PSRs, is subject to diurnal and seasonal temperature changes which can affect the mobility of volatiles on those timescales. If access to a PSR is not available, such measurements at a documented micro-cold trap may provide valuable initial information.

Investigation 2c-2: Subsurface temperatures—The character and structure of the regolith at the lunar poles is unknown. Accurate measurement of subsurface temperatures is critical to document and understand the subsurface ice stability regions which are predicted using thermal modeling coupled with LRO Diviner surface temperature observations. *In situ* temperature measurements are important to validate these models and allow for extended volatile distribution prediction maps with higher confidence, thereby improving our understanding of subsurface volatile distributions. Subsurface temperatures at strategically selected sites at resolution of 1 degree or better across depth intervals of 10-20 cm down to depths of 1 m are optimal. Temporal sampling over a lunar day/night cycle is ideal. Initial subsurface temperatures can be collected during the Artemis III mission, however temporal spacing over one lunar rotation requires more time than is available by the crew on the lunar surface. The deployment of long-term subsurface temperature probes to relay data over time is required to meet the temporal requirement for data collection. Adequate instrument dwell times are also important for accurate subsurface temperature measurements. Initial *in situ* measurements coupled with longer term monitoring via a deployed instrument package are required.

Investigation 2c-3: Determine the compositional/physical properties of H-bearing species of the regolith as a function of time—There are few quantitative data regarding the expected volatile movement and transport across the Moon and within the polar regions. The rates and abundances of various volatile species' transport must be determined *in situ* by measuring the volatile species' variations with time, for both undisturbed as well as exposed surfaces near and in PSRs as well as variations in surrounding exosphere and the dust environment. *In situ* measurements and the emplacement of long-lived instrument packages on the Moon will allow for the measurement of temporal variations in volatile components associated with undisturbed surfaces. Similarly, temporal documentation of variations of subsurface volatiles exposed during Artemis III (for example along a trench) is desired using sensors that capture hydration changes in a spatial context across the exposure.

Goal 2d: Understand regolith modification processes (including space weathering), particularly deposition of volatile materials in the near-surface—The lunar poles provide the optimal environment to evaluate surficial OH/H_2O associated with the solar wind and the role of space weathering on the deposition of volatile materials. By evaluating the speciation of near-surface hydrogen in the polar regions, we can understand effects of volatile processes that affect surface materials and regolith evolution.

Investigation 2d-1. Speciation of surface hydrogen—The lunar surface is a dynamic environment exposed to the solar wind, UV, and other radiation, and subject to space weathering processes of exposed and derived surface materials, including volatiles. Measurements to characterize these products and space weathering processes and effects can be performed on the Artemis III mission outside of the landing zone (where the surface is disturbed and likely contaminated). Increased mobility is optimal for improved contamination control, although astronaut walking distance is likely sufficient for initial measurements. Uppermost soil samples are required from a suite of diverse, well documented terrain with *in situ* volatile measurements before and after sampling. No subsurface access is required. Measurements and samples both in sunlight and shadow are preferred.

Goal 2e: Learn how water vapor and other volatiles are released from the lunar surface and migrate to the poles where they are adsorbed in polar cold traps—Not all lunar volatiles are expected to remain static and evidence suggests some are likely to be mobile across the lunar surface. Sources and sinks of water or hydrated materials migrating from mid-latitudes into polar regions and collecting in cold traps as deposits are not well constrained. In particular, volatile transport processes across the Moon and timescales must be studied with more globally relevant data.

Goal 2f: Understand the impact of exploration on the lunar volatile record across the surface—Activity on the lunar surface (both robotic and human) will inevitably alter the current natural state of the surrounding region. Such activities may include, but are not limited to, the effects of HLS rocket exhaust during lunar lander and ascent activities and degassing of astronaut spacesuits during EVA activities. Such exploration-induced effects should be measured in terms of character and modification of volatile composition, form, and distribution on the lunar surface. In addition to characterizing the human-induced variations, scientific questions to be addressed by these measurements include determining the broader nature of volatile adsorption in polar regolith, constraining the rate of sublimation of cold-trapped volatiles, and measuring the spatial and temporal variability of exospheric and surface adsorbed volatiles.

Investigation 2f-1: Identify exploration-induced variations on volatile composition, form, and distribution on the lunar surface during sample collection and transport, during curation and analysis, and from landed activities—Measurements to characterize the impacts of lunar surface exploration should be made in vicinity of the Artemis III lander, including measurements at varying distances from the site(s) of surface mission activity. *In situ* measurements as well as the deployment of long lived instrument packages are recommended to characterize both initial and temporal changes in the lunar polar volatile environment as well as to assess environmental impacts during and after lunar ascent from the surface.

5.3 Interpreting the Impact History of the Earth-Moon System

The surface of the Moon provides an exceptional record of impact crater formation extending from the earliest period of the Solar System to the present day (e.g., Stöffler et al., 2006). This lunar impact history is relevant not just to untangling the geologic evolution of the Moon, but to the Solar System as a whole. For example, Earth's ancient impact record has been largely destroyed by weathering, erosion, and plate tectonics, but the Moon's close proximity means that its impact record provides a guide to the terrestrial bombardment history as well as its own (e.g., Neukum and Ivanov, 1994). The Moon is also the touchstone for the rate of impacts across all the other terrestrial bodies; returned lunar samples linked to specific geologic units give an absolute calibration for crater accumulation rate on its surface, which can be extrapolated throughout the inner solar system with appropriate scaling (e.g., Ivanov, 2001; Marchi et al., 2009; Le Feuvre & Wieczorek, 2011; Schmedemann et al., 2014). However, this crater counting calibration currently depends on the ages determined from the returned Apollo samples, which were collected in a narrow nearside equatorial zone and are not a fully representative of the Moon as a whole. Therefore, better establishing the history of the Moon's early impact bombardment, its magnitude, form, and duration, has implications for our understanding of the ages of all other terrestrial planetary surfaces.

Despite the critical importance of the sample-calibrated impact chronology on the Moon, there remain gaps in our understanding of the lunar impact flux. In particular, the impact rate during the period >3.9 Ga remains poorly constrained. The large number of impact basins that formed prior to Imbrium basin has led to the hypothesis that the Earth-Moon system experienced an intense impact cataclysm (or Late Heavy Bombardment) during the period from ~3.9-4.1 Ga (e.g., Tera et al., 1974). The form of the impact flux on the Moon during this early period is poorly known and has major implications for understanding the dynamical evolution of the Solar System as a whole (reviewed, e.g., in Bottke and Norman, 2017; Zellner, 2017). In the past two decades, there have been numerous competing ideas about whether the impactors that formed the large impact basins on the Moon during this period came from the inner or outer Solar System as well as the timing of the major basin-forming events. For example, the migration of the giant outer planets has been proposed as a mechanism for a basin-forming impact cataclysm, thus, a better understanding of the early bombardment history has implications for our understanding of the outer planets as well. Given its Solar System-wide importance, many past studies, including multiple Planetary Decadal Surveys, have concluded that obtaining samples that constrain the formation age of early lunar basins is thus of the utmost scientific importance. This includes obtaining an absolute age estimate for the South Pole-Aitken basin (SPA), which is the oldest and largest known lunar impact basin and anchors the lunar impact basin record.

There are also other open questions about the impact rate in the Earth-Moon system, including the more recent impact flux and its variability in space and time. One cause of this uncertainty is the limited samples constraining the cratering chronology in the Apollo collection subsequent to 3 Ga. This uncertainty after 3 Ga age means that the age of the youngest widespread volcanic units on the Moon is not established with certainty and could be 1 Ga or 2 Ga. Measurements of the rock abundance surrounding craters have led to the suggestion that the lunar cratering rate has increased by a factor of 2-3 in the last 250 Myr relative to the preceding 750 Myr (Mazrouei et al., 2019). Likewise, crater size-frequency measurements of individual craters have been used to infer possible lulls or spikes in the cratering rate on the Moon, perhaps due to the formation of asteroid families near orbital resonances that enhance the ease of impactor delivery to the inner

Solar System (Kirchoff et al., 2021). Progress on these topics will benefit from careful field geology on the Moon and return of new samples for radiometric analysis. Artemis will be an opportunity for this type of study in part because landing near the South Pole will provide access to rocks and regolith far from those obtained by earlier sample return missions (Apollo and Luna). This will help provide insights into the impact history of the Moon at locations in the highlands distinct from the samples of Procellarum KREEP terrane from Apollo (e.g., Jolliff et al., 2020). Sample collection that allows for the diversity of local and regional impact events to be assessed and for potential relicts of impactor material to be identified are necessary for understanding these important themes.

Goal 3a: Test the cataclysm hypothesis—The cataclysm hypothesis, also known as the Late Heavy Bombardment, suggests that ~3.9-4.1 Ga ago the Moon and the rest of the inner Solar System suffered from an increased flux of impacts from large, basin-forming projectiles. This hypothesis is largely built upon the impact reset ages of samples returned by the Apollo missions that clustered around 3.9 to 3.85 Ga (e.g., Tera et al., 1974). However, the limited region sampled by the Apollo landing sites represent a potentially biased set that may be dominated by influence from the ages of the near-side basins (particularly Imbrium; e.g., Haskin et al., 1998) and therefore not reflective of the early bombardment of the entire lunar crust. Alternative hypotheses suggest a bombardment history with a slower decline in the impact flux after the formation of the Moon, potentially punctuated by a later small increase (or several) in the impact flux, rather than the steep initial decline followed by a sharp spike suggested by the cataclysm hypothesis. As already described, understanding this early impact history has important implications for our understanding of the early evolution of Earth, the development and evolution of other bodies in the inner solar system, as well as the potential migration of outer planets.

Investigating the lunar cataclysm hypothesis therefore is not just a lunar science goal, but a fundamental science goal for the entire Solar System as well, in particular for understanding surface conditions of early Earth and Mars. It is clear that the effects of large impacts are broad and have significant environmental consequences for Earth (e.g., Collins et al., 2005). For this reason, it was once thought that the cataclysm may have frustrated habitation of the early Earth (Maher and Stevenson, 1988), but these more recent observations coupled with numerical models (Abramov and Mojszis, 2009) have disputed that idea. Indeed, recent studies (Kring et al., 2020a, b) have shown that impact-generated hydrothermal systems related to the Chicxulub impact can support life and support an impact origin of life hypothesis. Measurements that clarify the nature of the lunar cataclysm, and whether the impact rate was such that it aided or frustrated life, thus have important implications for our understanding of early life on Earth and elsewhere. Impact-induced hydrothermal systems (e.g.,Osinski et al. 2010) are potentially not just a terrestrial phenomenon but may also have arisen on early Mars (e.g., Abramov and Kring, 2005; Osinski et al., 2013), so the early impact history of the Moon has broad astrobiological importance far beyond just the Earth-Moon system.

In order to test the validity of these hypotheses, samples must be returned that contain material from basins that formed prior to Imbrium. South Pole-Aitken is recognized as marking the beginning of the basin record. An age of SPA of ~4.1 Ga would firmly support the cataclysm hypothesis by forcing all observed lunar Pre-Nectarian and Nectarian basins to fall between 4.1 and 3.9 Ga. Alternatively, a comparatively ancient age for SPA (~4.3 Ga) would not prove or disprove the cataclysm, but would provide an important anchor for when the Moon could retain large basins, and therefore provide important information about its thermal evolution, as well as serve as the base of the Moon's geologic record. If SPA is comparatively ancient, testing the later form of the cataclysm would ultimately require obtaining samples and dating additional Pre-Nectarian or Nectarian basins.

Investigation 3a-1: Identify basin impact melt, impact ejecta, and exogenous (impactor) material in lunar samples to address the hypothesized Lunar Cataclysm—This investigation encompasses field geology and sample collection to collect a diverse set of basin impact-related samples such as impact melt and regolith breccias, the latter of which may contain relicts of the impactors delivered to the Moon. South polar landing sites (south of -84°) will be well outside the expected transient crater diameter for both SPA and other early basins, and therefore far from the most likely outcrops of basin impact melt. Nonetheless, there is still a probability that impact material from SPA or other basins was transported into the region as ejecta (e.g., Marchi et al., 2012) as well as in later impact events. In the south polar region, astronauts should seek to collect samples from craters formed throughout the basin-forming epoch (Pre-Nectarian, Nectarian, and Imbrian-aged basins). This would be enhanced by detailed remote observation studies of the landing site to select potential boulders for sample collection and field observations.

This investigation would seek to return samples that record the age of identifiable basins. Moreover, studies have shown (e.g., reviewed in Joy et al., 2016) that exogenous material delivered to the lunar surface by impacts can be preserved within regolith breccias. This could elucidate the source and nature of the early impactor population (e.g., rocky/asteroids vs. icy/comets; Morbidelli et al., 2018) as well as potentially a source for near-surface lunar volatiles (see investigation 2b-3) if early impactors were ice-rich. Moreover, identifying the potential source of the impactors during this time period would provide a fundamental constraint to dynamical models of early impactors (e.g., late vs. early instability) as well as have astrobiological implications for early Earth and Mars. Samples collected by the Artemis III crew must be carefully examined in a terrestrial laboratory setting to determine the isotopic ages as well as identifying exogenous material, and not all regolith breccias or impact melt breccias will contain information necessary to evaluating the Cataclysm hypothesis, but may instead represent younger impact events that could address Goal 3b.

Impacts melts or ejecta specifically from the SPA basin may be recognizable at a South Polar landing site on the basis of geochemical differences with other highlands rocks. However, missions that select landing sites directly for the purpose of returning samples from the interior of SPA (or other targeted basins) would have a significantly higher probability of addressing the science aims for this specific investigation, so steps made toward this investigation by Artemis III do not act as a replacement for other possible missions (human or robotic) to SPA (or other targeted basins).

Goal 3b: Understand changes to Earth-Moon bombardment in the post-basin era—In the period following the Imbrium impact event, the lunar cratering chronology has provided the basis for understanding the impact flux in inner Solar System. Despite this critical importance, the Apollo and Luna samples provide absolute age calibration points at only ~10 locations, spaced closely together on the lunar near-side (Stöffler et al., 2006). In addition, the absolute age calibration is much stronger in the period from 3 to 3.8 Ga compared to later times. Large young basins like Schrödinger and Orientale may be potentially useful targets for absolute dating in this period, because they affect wide areas of the Moon and also have well-defined surfaces for crater statistics. Additionally, in the lunar regolith, both impact glass (e.g., Zellner, 2019; 2020) and impactor material (e.g., Rubin, 1997; Zolensky, 1997; Joy et al., 2012, 2020) have been studied in detail and provided a fascinating picture of what objects have struck the Moon over time; the record from the Apollo sites, however, is narrow, incomplete, and not totally understood, and the lunar meteorite collection is also incomplete. Finally, direct measurements of lunar impact bombardment at the present-day are also a useful basis for understanding the impact rate and how it may vary with space and/or time.

Investigations that will expand our understanding of changes in the impact flux in the post-basin era from returned samples include sampling specific geologic units or large craters to determine their formation timing; locating impact glass in the regolith at locations far from the Apollo sites; identifying impactor material (including possibly impact-delivered volatiles) in returned samples; and deriving ages for additional mare units distinct from those in the Apollo and Luna collections. Additionally, investigations of the modern impact flux would benefit from monitoring experiments either at the surface (e.g., seismometers, ejecta and/or micrometeorite particle detectors), in orbit, or both.

Investigation 3b-1: Refine the post-basin impact flux, including up to the present—Similar to Investigation 3a-1, this investigation would incorporate pre-mission remote observations, field geology, and sample collection to return material related to impact events in the post-basin-forming epoch (late Imbrian, Eratosthenian, Copernican). Remote observations, such as high-resolution images from the Lunar Reconnaissance Orbiter Camera (LROC) as well as spectra (e.g., Moon Mineralogy Mapper, M3) will aid in potentially identifying boulders with clear relationships to nearby craters for the crew to visit on the surface for sample collection. Along with larger rocks, rake samples optimized to collect rocklets (fragments >1 cm in diameter) would provide a wealth of samples to supplement the boulder samples, with some portion of the rocklets likely representing melt fragments. Crew should collect larger samples of impact melt as well as regolith breccias to allow for radiometric dating of impact events as well as identification and characterization (geochemical and isotopic studies) of relict impactor material. Collection of a diverse set of impact-related samples is critical and should be considered in pre-mission planning. The current, modern-day impact flux near a south polar landing site is also of scientific importance. Model predictions exist for the modern impact flux in polar regions and how these may differ from equatorial latitudes, but there are few data that validate these calculations. This could be accomplished by regolith exposure age measurements from collected samples, or with seismic monitoring measurements synergistic with those that would address Investigations 1a-3 or 7m-1.

Goal 3c: Understand the impact history of the landing site—Impacts are ubiquitous as a process at all scales on the lunar surface, and the geology of any landing site will be deeply affected by the sequence of cratering that occurred. Unraveling this complex history will be an important part of interpreting the samples gathered and returned by Artemis III. Field geology investigations by the astronauts will also allow a deeper understanding of impact processes such as impact crater morphology and modification processes that would play a driving role in analyzing the geologic record of impact events at the site (and therefore the returned impact-generated samples); this links directly with Objective 1 by examining materials brought up from depth within impact basins (e.g., central peaks and peak rings) for insight into lunar crust composition and evolution. Samples that can be traced to specific impact craters can be used to date these individual impact craters or basins, which will help improve models for the Moon's cratering chronology as discussed above. Specific large craters and basins from which material might be found near the South Pole include, but are not limited to, SPA, de Gerlache, Orientale, Schrodinger, Shackleton, and possibly Tycho (Denevi and Robinson, 2020; Jolliff et al., 2020). Such an approach will also potentially enable a better understanding of the sample provenance, depth of excavation, and exposure history, and the effect on delivery and/or modification of volatiles in the south polar region.

Investigation 3c-1: Determine the sequence of individual craters and basins that influence local, regional, and global stratigraphy at the Artemis III landing site—The detailed nature of this investigation will be landing site specific, but will encompass the field geology, geologic mapping, and site characterization that will come from exploring any site. The observations that astronauts make while coring, trenching, and/or making geophysical measurements that establish regolith stratigraphy will help understand a locations, impact history, as will the determination of the provenance of boulders and/or outcrops (as described for investigation 3a-1 and 3b-1, above). Ultimately establishing the detailed impact geology of a landing site will also be critically enabled by sample analyses, including sample provenance investigations that assess the origin of collected material. This investigation requires the collection of a diverse set of samples in order to adequately capture a variety of local, regional, and global impact events. The information gathered in this investigation is directly synergistic with Investigations 3a-1 and 3b-1, and Goal 1e.

5.4 Revealing the Record of the Ancient Sun and Our Astronomical Environment

Planets are modified by their interaction with the space through which they travel, and although that space is often described as empty, it is not. Meteoritic and cometary bombardment is thought to change the chemistry of planets as a whole and potentially to provide volatile elements that are critical for life as we understand it (Albarede, 2009). The Sun provides heat to the bodies surrounding it, affecting their thermal, chemical, and biological evolution. Particles derived from the Sun – solar wind and solar energetic particles – also permeate the solar system, in some cases adding hydrogen and other elements to planetary bodies, and in other cases stripping those elements from the atmospheres of the planets (Melosh and Vickery, 1989). The Solar System as a whole is exposed to high-energy radiation from external sources, such as galactic and extragalactic cosmic ray particles and electromagnetic radiation from gamma-ray bursts.

The airless Moon, with its ancient crust, serves as a witness plate that captures processes taking place in space. The interaction of the solar wind, cosmic rays, and meteorite bombardment with the regolith on the surface of the Moon changes the chemical, isotopic, and/or petrographic makeup of that regolith. By studying preserved paleoregolith horizons one can construct a timeline or history of processes that are important to the study of many of the bodies in our solar system (including the Sun).

Goal 4a: Understand the history of the Sun, including the composition and flux of the solar wind—Lunar regolith incorporates solar wind, and therefore studies of regolith and preserved paleoregolith, in combination with precise and accurate geochronology of those horizons, can be used to construct a record of how the composition and flux of the solar wind have changed with time (Wieler, 1998). This information can be used to inform studies of our Sun in addition to studies of planets. The specific investigations that can be used to achieve this goal begin with the collection of well-preserved and well-characterized samples of lunar regolith of different ages. Stable isotope measurements and micro- to nano-scale petrographic studies of these regolith materials are then made in concert with precise and accurate geochronology of those horizons to build histories of solar wind intensity and chemistry.

Goal 4b: Understand the record of solar energetic particles, cosmic rays, gamma-ray bursts, and supernova—Lunar regolith is exposed to high-energy particles originating from the Sun as well as from outside the solar system (Reedy and Arnold, 1972). Measurable isotopic variations are generated when that radiation interacts with atoms on or near the surface of the Moon, and thus the Moon potentially contains a record of those processes that extends back several billion years (Marti et al. 1977; Crozaz et al. 1977). Such a record can be built on a framework of detailed geologic context and precise regolith chronometry, with isotopic measurements of regolith samples with a wide range of ages.

Goal 4c: Understand changing compositions of impactors with time, and the nature of the early Earth—Lunar regolith contains approximately percent-levels of materials derived from meteoritic infall, including the possibility of terrestrial materials from the early Earth (Bellucci et al. 2019). Variations in abundance, chemistry, and petrography of meteoritic materials in regolith of different ages provide essential information about the long-term variability of meteorite influx. Materials from the early Earth could inform studies of the formation of the Earth, the building of the early crust and initiation of plate tectonics, or the development of life (Armstrong et al. 2002). Petrographic and geochemical studies of meteoritic clasts derived from multiple regolith samples with a wide range of ages, obtained via coring or by sampling regolith of different ages exposed at or near the surface, can be used to satisfy these goals.

Goal 4d: Understand the long-term variability in the solar constant—The intensity of solar radiation as a function of time controls heat input to the terrestrial planets and therefore is an important parameter in studies of planetary thermal evolution. Detailed, long-duration heat-flow measurements can be used to determine variability in the solar constant over periods of tens to hundreds of years (Miyahara et al. 2008). These measurements can be made by monitoring temperature profiles in boreholes through the regolith.

5.5 Observing the Universe and the Local Space Environment from a Unique Location

A robust human and robotic exploration program provides unique opportunities to employ the Moon as a platform for high-priority astrophysics, heliophysics, and Earth science investigations. Some of these proposed investigations, although they could be a part of Artemis III, could also be implemented through the Commercial Lunar Payload Services (CLPS) and Lunar Gateway independent of Artemis III. Other investigations that are not part of CLPS may still be best achieved robotically rather than through the human exploration program, and other NASA opportunities such as Discovery, Heliophysics and Astrophysics Explorers, Solar Terrestrial Probes, Living With a Star, Earth Venture, and SIMPLEX (Small Innovative Missions for Planetary Exploration) may be the appropriate route to implementation. Finally, some directed NASA missions may perform certain investigations on satellite and other platforms independent of the lunar program. Still, the human exploration program opens the door to numerous potential investigations that either will not be implemented through other programs and/or require a human presence on the Moon.

The Moon's position relative to Earth's magnetosphere makes it an excellent location to study the solar wind, characterize the effects of the Moon on the local plasma environment, and perform observations of the Sun and extra-solar system planets over a broad frequency spectrum. Astrophysical studies may be performed from the Moon, especially at frequency ranges not favorable for space-based telescopes (Bassett et al., 2000). In particular, the lunar surface offers unique opportunities for long wavelength radio astronomy from the radio-quiet far side of the Moon (Burns, 1988).

Goal 5a: Astrophysical and Basic Physics Investigations using the Moon—For astrophysical observations, the lunar surface offers unique advantages over other sites. Among these advantages are a large surface and a large mass that can provide shielding, for example from noise originating at Earth. One such example that utilizes the far side of the Moon involves imaging the 21 cm electromagnetic radiation spectral line to study the "Dark Ages" of the universe, the period during which the first stars began to shine, free from radio noise generated at Earth (Jones et al., 2015). The Moon may also play a critical role in tests of general relativity (and possibly alternative theories of gravitation) by a high accuracy determination of the lunar orbit, perhaps by deploying retroreflectors for laser ranging from Earth (Mueller et al., 2019). Furthermore, the gravitational waves predicted by general relativity could be detected by interferometers that benefit from, for example, the low seismic activity characteristic of the lunar surface. The Moon may also serve as an optical bench for interferometers allowing one astronomical unit target resolution.

Goal 5b: Heliophysical Investigations Using the Moon—Heliophysics investigations using the Moon generally fall into two broad categories, those that employ the Moon to perform observations of the various non-lunar plasma environments and those that study lunar electrodynamics. Investigations of lunar electrodynamics include the formation of lunar surface potentials, particularly across lit to shadowed boundaries like those formed at the terminator and near permanently shadowed regions (Manka, 1973), studies of solar wind access such as in the lunar wake and at polar craters (Farrell et al., 2008), and studies of lunar crustal magnetism, particularly those that may limit solar wind access to the surface possibly affecting space weathering and albedo (Garrick-Bethell and Kelley, 2019; Poppe et al., 2016). Note that linked to lunar electrodynamics is its effect on charged dust behavior which is covered in detail in Objective 7 on Exploration Hazards.

Investigations focusing on the various non-lunar plasma environments include studying the terrestrial magnetosphere, such as the magnetotail which the Moon traverses every orbit, solar wind studies, studies of the Sun including far-side radio frequency observations, and space weathering studies, including impinging radiation. In addition, remote sensing of the Earth's magnetosphere through energetic neutral atom (ring current), UV (exosphere), FUV (ionosphere/mesosphere and auroral regions), EUV (plasmasphere), and soft X-ray (magnetosheath) imaging and observations of heliospheric structure and phenomena may be enabled by a lunar platform.

Note that some of these heliophysics investigations will be addressed by selected missions (for example the Interstellar Mapping and Acceleration Probe – IMAP – for heliospheric imaging), via CLPS activities (for example some dust studies) or via the Gateway (for example the Heliophysics Environmental and Radiation Measurement Experiment Suite – HERMES – for space weather studies in the cis-lunar environment).

Investigation 5b-1: Near-Lunar Electromagnetic and Plasma Environment—The interaction with ambient plasma and incident solar ultraviolet (UV) radiation causes the lunar surface to become electrically charged (Manka, 1973; Farrell et al., 2007). This creates possibly complex electric field configurations with the sunlit areas generally charging positive because of photoelectron emission from the surface and shadowed regions becoming negatively charged because of the high mobility of plasma electrons. This complex interaction depends on many factors including variations in solar UV intensity, the plasma moments, surface properties like secondary electron emission, topography, and the presence of magnetic anomalies. Clearly, the plasma conditions depend on both the location of the Moon in its orbit – solar wind, magnetosheath, plasma sheet, and magnetotail lobe – and the location on the lunar surface, for example the lunar wake. These factors determine the electric field configuration that affects the behavior of charged lunar dust. In general, the surface electric potential is confined to a near-surface sheath region.

Significant uncertainties remain in lunar surface charging processes, and relatively little is known about either spatial or temporal variations in the charge density, electric potential, or field strength. Observations needed to characterize the near lunar plasma environment can be carried out both from orbit (providing a global-scale view) or from the surface (providing a complementary local view). Coordination of measurements from orbit and the surface can reveal connections between processes on different scales, providing both the global boundary conditions, the lunar plasma environment, and effects occurring at the local level like surface secondary emission characteristics (Halekas et al., 2009). Not every point on the lunar surface experiences the same conditions; for example, locations near the poles will be quite different from those nearer the equator. Hence, it is advantageous to deploy surface-based instrumentation over a wide range of lunar sites.

Goal 5c: Use the Moon as a platform for Earth-observing studies—As it does for heliophysics and astrophysics investigations, the Moon supplies a convenient platform for Earth science. Note that the Moon's orbit at 60 Earth radii is about four times closer to the Earth than is the Lagrange L1 point, a popular location for spacecraft such as NASA's Deep Space Climate Observatory (DSCOVR). Consequently, it is likely that observations from the Moon will have higher resolution than would similar observations made at L1. Myriad science investigations targeting topics such as lightning, Earth's albedo, atmosphere, and exosphere (which is also a heliophysics investigation achieved through UV imaging), the oceans, infrared emission, and radar interferometry may be accomplished from the surface of the Moon. The Moon also offers a unique vantage point for full-disk observations that can help advance investigations of Earth as an exoplanet, focusing on key signatures of life to enhance current terrestrial exoplanet observation and characterization methods from ground based and space based observatories.

5.6 Conducting Experimental Science in the Lunar Environment

The Moon has a unique combination of environmental characteristics not collectively attainable on Earth that support establishing experimental boundary conditions that may be valuable and necessary to the investigation of high priority scientific questions (LEAG, 2016). For example, one significant and unique environmental characteristic is the long-duration, steady 1/6 g environment present at the surface of the Moon. Many physical and biological systems are known to be sensitive to both the magnitude, direction, and temporal ("g-jitter") characteristics of gravity. Although the space radiation environment on the lunar surface (principally a combination of galactic cosmic rays, solar energetic particles, and commensurate neutron albedo) is not unique, in combination with 1/6 g it becomes so. This is also true with respect to the plasma (and plasma-regolith interactions on an airless body) and vacuum (hard vacuum combined with near infinite pumping speed) environments found on the Moon. Therefore, possibilities exist for unique experiments and investigations to be performed on the lunar surface in coordination with other Artemis activities and surface elements.

NASA's Division of Biological and Physical Sciences (BPS) focuses on using the spaceflight environment to conduct experiments that cannot be conducted on Earth (NASA, 2020). Biological sciences are discussed in Objective 7 (Section 5.7). Physical science research that could be accomplished on the lunar surface includes biophysics, combustion science, complex fluids, fluid physics, fundamental physics, and materials science. Many of these possible investigations (in the LER, and listed in the Science Traceability Matrix for Artemis III, Table 1), however, require experimental facilities that need volume in a pressurized habitat and diagnostic tools and equipment, such as those found in the Fluids and Combustion facility aboard the International Space Station. These facility-based investigations are beyond the scope of the Artemis III mission, but will be important science objectives for the Artemis Base Camp.

If the Artemis III mission is supported with pre-deployed equipment and payloads by a robotic lander, such as a CLPS lander system, some physical science investigations could be conducted on the lunar surface, including understanding the behavior of granular media in the lunar environment, studying and assessing effects on materials of long-duration exposure to the lunar environment, and creating lunar concrete out of regolith materials. However, it is not currently known if such a CLPS mission will be available for the Artemis III mission, and these objectives will need to be reassessed if one becomes available.

Goal 6a: Investigate and characterize the fundamental interactions of combustion and buoyant convection in lunar gravity—Fundamental combustion-convection issues have direct bearing on practical problems of fire safety and control. The Moon provides a platform for investigating behavior at sustained low gravity. As an example, the diffusion coefficients for hydrogen atoms and molecules through mixtures of species is one of the most sensitive parameters in combustion systems near the limits. We need much better values for these in different environments for model development and verification to assist the feed-forward aspect of going to Mars. Other investigations include understanding flame structure and instabilities near combustion limits, and large, lean weakly buoyant flames in hydrogen and methane, and testing multidimensional dynamic models of flame phenomena.

Goal 6b: Perform tests to understand and possibly discover new regimes of combustion—New regimes of combustion have been demonstrated in microgravity conditions. This goal primarily involves exposing reactive mixtures or existing flames to different conditions in sustained low gravity, looking at what happens, and comparing results with theory and numerical simulations, looking for consistency with earth-gravity and zero-gravity results. Models exist that can compute this, although they have not yet been applied to rarefied, highly reactive flows. The results of this goal are of fundamental interest that may be employed to refine combustion processes in general. Investigations on the lunar surface include studying flame balls, rarefied gas combustion, and how large reactive mixtures or flames behave when exiting to a vacuum or very low atmospheric pressure.

Goal 6c: Investigate interactions of multiphase combustion processes and convection in lunar gravity—This goal yields information of direct benefit to the design of safe systems for lunar environments as well as providing fundamental information that will benefit feed-forward efforts for the exploration of Mars. Numerical simulations have predicted that extinction of pool fires by water mist behaves differently in earth and lunar gravities. Verifying and understanding this result will give insight into fundamental differences in balances between buoyancy and other forces. It is also important information for designing fire-extinction systems. Investigations include understanding the interaction of water mist with diffusion flames, and the process of soot formation in lunar gravity.

Goal 6d: Use the unique environment of the lunar surface to perform experiments in the area of fundamental physics—The stability of the lunar platform in terms of low-level seismic activity and ultra-high vacuum provide a unique environment for experiments that advance our understanding of physical laws, nature's organizing principles, and how these laws and principles can be manipulated by scientists and technologies to benefit humanity on Earth and in space. Investigations include searching for gravitational radiation, testing the theory of general relativity, experimenting with atomic clocks, and conducting particle physics research, such as dark energy and dark matter.

Goal 6e: Obtain experimental data to anchor multiphase flow models in lunar gravity— The surface of the Moon allows long-term access to lunar gravity and length scales unavailable in conventional spacecraft. The refinement of multiphase-flow models enables the efficient design of lunar systems and permits feed-forward prediction capability for Mars exploration. Investigations include testing simple two-phase flow through straight channels at different inclinations and through porous media/packed beds, and assessing the efficacy of boiling heat transfer in lunar gravity.

Goal 6f: Study interfacial flow with and without temperature variation to anchor theoretical/numerical models—Interfacial flows assume a greater importance in the presence of reduced gravity, potentially enabling alternate liquid transport mechanisms. These will enable the more efficient design of lunar systems and permit feed-forward capability for the design of systems for Mars exploration. Investigations include studying low-Reynolds-number dynamic wetting in the presence of temperature gradients typical of the lunar environment and lunar gravity, validating the relative importance of capillary-driven versus buoyancy-driven flow in various geometries, and studying the behavior of liquid wicking under lunar gravity.

Goal 6g: Study behavior of granular media in the lunar environment—The development of *in situ* resource utilization schemes requires knowledge of the behavior of granular media in the absence of atmosphere on the lunar surface. Likewise, lunar dust is ubiquitous, leading to potential degradation of radiative heat transfer and optical components through the fouling of surfaces. Investigations include obtaining experimental data on gravity-driven, dense granular flows, such as flows out of a bin, corresponding to Earth-based design methods; measuring the impact of accumulated lunar dust on exposed radiative, habitat, transportation, suit and optical surfaces, and understanding how the electrical charge of the dust is important to this accumulation (also, see science goal 7k); and studying the chemical reactivity of lunar dust on non-human biological model systems to validate the Earth based assessment of lunar dust toxicity and the proposed Permissible Exposure Limit (PEL) to lunar dust.

Goal 6h: Investigate precipitation behavior in supercritical water in lunar gravity— Supercritical water applications are becoming more widespread in industry. The presence of secondary phases shifts the critical point, impacting performance. Understanding critical-point shift under lunar gravity will yield greater understanding applicable to 1-g, Mars-g, and reduced-g applications. Investigations include measuring salt deposition rate on heated surfaces in supercritical water-salt solutions with and without flow, and assessing the effects of Lewis number on homogeneous and heterogeneous salt precipitation in supercritical water-salt solutions.

Goal 6i: Investigate the production of oxygen from lunar regolith in lunar gravity—Techniques proposed for oxygen production from lunar regolith are gravity dependent. Methods for electrolysis of molten material result in buoyant convection and bubble transport. The behavior of fluidized-bed reactors in lunar gravity also need confirmation. Investigations include studying separation behavior within melt of solids and bubbles during oxygen production using electrolysis, and determining multiphase heat-transfer schemes required for oxygen production employing regolith reduction.

Goal 6j: Investigate the behavior of liquid-phase sintering in lunar gravity—Liquid-phase sintering processes are gravity-dependent because particles are embedded in a liquid phase. For low solid volume fraction, sedimentation of solids, as well as the behavior bubbles formed due to outgassing, result in different structural properties for materials produced in microgravity. Study of the process conducted in lunar gravity will help to refine theoretical models, pointing the way to efficient use of the technique on the Moon as well as supporting the feed-forward goal of exploring Mars.

Goal 6k: Study and assess effects on materials of long-duration exposure to the lunar environment—Exposure to extreme temperatures, micrometeoroid bombardment, and radiation affect the long-term integrity of materials on the lunar surface. Investigations include analysis of human-emplaced materials from the Apollo era, and human/robotic emplacement of controlled material samples for evaluation in the lunar environment.

Goal 6l: Study the production of lunar concrete samples in the lunar environment—Construction of habitats, shelters, and prepared surfaces will be needed for long-term sustainable operations on the Moon. There are scant data regarding the creation of a concrete with actual lunar regolith, and the durability of that concrete in the lunar environment. Early investigations include studying the mixing of materials delivered from Earth with lunar regolith, the use of molds, and lunar concrete performance and durability, and also studying the lunar environment exposure of premade concrete samples with lunar simulant.

Goal 6m: Study material flammability in the lunar environment—Limited existing data and models suggests that material flammability in partial gravity may be a worst-case condition for fire safety.

Goal 6n: Study the conversion of water-ice to gaseous hydrogen and oxygen, and liquefaction of gasses for propellant storage—Water ice in permanently shadowed regions, or in the polar subsurface is an important potential resource, and this goal focuses on the processing of that ice. Investigations will include examining the influence of gravity on solid-liquid phase change of water ice including sedimentation of regolith in the liquid water, and studying the buoyancy driven flow of hydrogen and oxygen bubbles in partial-g during electrolysis, and the condensation of hydrogen and oxygen in partial-g during the liquefaction process.

Goal 6o: Study the water management in lunar plant growth systems—Plant growth systems will be needed for long-term sustainable operations on the Moon, as part of a bioregenerative life support system. Early investigations include studying the stability of flow through a soil simulant and/or lunar regolith, and evaluating aeration and hydration of plant roots as a function of the capillary uptake vs gravity induced drainage, and examining the stability of flow in hydroponic systems within capillary-dominated channels in that have compliant obstructions, and studying the uptake and evaporation of water in a capillary based system.

Goal 6p: Study pool and flow boiling in the lunar environment—Investigations include examining the influence of gravity on phase change, heat transfer, vapor bubble growth, coalescence and departure, and studying partial gravity effects on vapor-liquid phase change, flow and heat transfer.

Goal 6q: Study two phase adiabatic flow in the lunar environment—Investigations include examining the effect of gravity on interfacial shear, wave and slug formation, droplet entrainment and deposition processes, and studying the effect of the gravity vector (magnitude and direction) on gas-liquid flows through various flow system components.

Goal 6r: Perform tests of lunar resource recovery of O, Al, Fe or Mg using ionic liquids—Investigations include understanding the effects of partial-g on the complex fluid flow and mass transfer that needs to occur for ionic liquids to work, and investigating the performance of different, community-proposed ionic liquids and the materials derived from this process and their usefulness for various applications.

Goal 6s: Perform tests of biofilms on various materials and the effect of biocide surface coatings on biofilms—Investigate the use of bacterial and fungal biofilm formation under lunar gravity on materials commonly used for surface habitats, and answer key questions about biofilm formation and mitigations, including effectiveness in spacecraft environment, safety concerns with any off-gassing, and equipment compatibility.

5.7 Investigating and Mitigating Exploration Risks

The exploration of the Moon via Artemis missions represents an opportunity to investigate the response of hardware, humans, and other organisms to an extreme environment. Following the eventual establishment of the Artemis Base Camp, we will be able to study how humans respond to a partial gravity environment for extended periods of time. Specifically, important questions and knowledge gaps concerning the impacts of deep space radiation alone and in combination with the reduced gravity of the Moon can finally be addressed. Despite the relatively short duration of Artemis III on the lunar surface (6.5 days), this initial exploration represents an opportunity to commence fundamental Investigations into how living systems respond to the lunar environment (e.g., 1/6th ge, deep space radiation) and how the space environment interacts with the area explored by Artemis III. The fundamental biology research studies enabled by the Artemis III mission will provide early pathfinder data and experience to guide the development of more complex studies and aid in defining the scientific instruments and technologies required to conduct subsequent investigations on the lunar surface. We will also be able to use the Moon for studies relevant to increasing our understanding of planetary protection, such as assessing the behavior of terrestrial contaminants introduced to the Moon by human exploration. The Artemis III mission is an opportunity to study the survivability of microbes inadvertently delivered to the lunar surface, and in turn determine the implications for exploration elsewhere in the Solar System.

Ultimately, these studies will provide knowledge that will inform preparation for both longer duration lunar missions, sustained living on the Moon, and missions to Mars. The NASA Artemis Lunar Exploration Overview, the Lunar Exploration Roadmap (LER, 2016) and a number of white papers submitted to the Artemis III Science Definition Team outline science Goals and Objectives relevant to understanding the exploration risks to humans in deep space that could be addressed by the Artemis III mission. No fewer than 13 Goals are called out under this Artemis Objective

(Table 1); however, the short duration of Artemis III precludes the opportunity for long-duration monitoring of the human system in response to the lunar environment. Here we highlight opportunities afforded by Artemis III to address the Goals under this Objective.

The biological science that can be accomplished on the Moon under a long-duration mission ranges from understanding the fundamental biological and physiological effects of the lunar environment on human health to understanding the consequences of long-duration exposure to lunar gravity alone or in combination with space radiation on biological systems, including those of model organisms, humans, and crop plants. Although the Artemis III mission will be limited in both duration on the lunar surface and research space allocated for experiments, passive or fully automated experiments can be designed and conducted that meet available resources, which would return valuable novel data. Also, the Artemis III mission includes the transit to and from the Moon in the deep space radiation environment and changes in gravity (i.e. Earth and Moon), which could enable important areas of research investigation. The first ten Goals of this objective entail the study of a diversity of biological systems, from humans, to model organisms to plants.

Goal 7a: Study the fundamental biological and physiological effects of the integrated lunar environment on human health and the fundamental biological processes and subsystems upon which health depend—The lunar surface is an ideal environment to investigate the effects of two of the five identified hazards to human health during space exploration: space radiation, and reduced gravity (the other three identified hazards are isolation and confinement, distance from Earth, and hostile/closed environments). Associated with these individual risks is the unknown risk of how a combination of space radiation plus reduced gravity affects biological systems. Studies can be conducted to investigate how physiological systems adjust to changes in gravity over the timeline of a mission (e.g. from microgravity to 1/6 ge to microgravity to 1 ge). In order to understand the impact of the lunar environment on biology, investigations using model biological systems, including cell culture systems (e.g. 2-D cultures, 3-D cultures, Tissue-on-a-Chip, and multi-physiological systems), simple single cell organisms (e.g. microbiology), and complex multicellular organisms (e.g. invertebrates and non-human vertebrates) must be used to conduct in-depth analyses that cannot be performed on human volunteers, which reveal changes to structures, functions, and intra-and inter-physiological dynamics. In combination with systems biology analytical methods and techniques, the underlying networks and mechanisms that cause and govern the higher level physiological changes can be identified. These same research considerations are applied to studying the impact of the lunar environment on plants. Key amongst these botanical studies is the investigation of crop plants from seed to mature plant. The findings from such studies would advance horticultural understanding for providing sustaining plant-based products for food and nutrition, as well as plant-based resources for life support systems and materials. Artemis missions provide important opportunities in space biosciences, starting with pathfinder microbiology (radiation exposure) and invertebrates (radiation alone or in combination with 1/6 ge) studies. In addition, packets containing seeds or dormant microbes (e.g. spores) may be left on the Moon for retrieval during later lunar missions in order to study the consequences of long term space radiation exposure on survival. The results from these studies may be compared to the data from the Space Biology Artemis I studies, BioSentinal, Earth-based analogs, and ISS to identify lunar environmental-specific effects and to build models that are predictive of biological responses and behavior. Finally, stand-alone measurements and characterization of the lunar radiation environment are essential for data interpretation informing the design of experiments. Investigations from an Artemis III mission could provide initial benchmark data of biological responses to this environment leading to longer duration and more complex studies.

Goal 7b: Study the key physiological effects of the combined lunar environment on living systems and the effect of pharmacological and other countermeasures—Goal 7a is cross-cutting to Goal 7b. It is essential to understand how biological systems behave and are affected by the lunar surface environment in order to characterize and validate countermeasures. Also, identification of key physiological effects requires understanding biological responses from an integrative systems perspective by studying individual physiological systems, the interactive dynamics between all physiological systems, and identifying underlying genetic alterations and biochemical and molecular networks and mechanisms (i.e. systems biology analyses). The identification and characterization of underlying mechanisms and network systems play an important role in discovering the key physiological processes that are altered by the lunar environment and aid in identifying biomarkers for diagnostics and specific targets for countermeasures, and understanding countermeasure effects, specific and side-effects. Questions, such as “what are the early changes that are predictive of and lead to eventual observable tissue changes and symptoms?”, “how early do changes at the molecular and biochemical levels occur, which eventually affect physiological morphology and functions?”, and “what are the changes at the genomic level (e.g. mutations, epigenetics)”, can be studied using systems biology analyses. Novel data and an initial baseline of data may be acquired from basic experiments using model biological systems.

Goal 7c: Evaluate consequences of long-duration exposure to lunar gravity on the human musculo-skeletal system—The approximate doubling of time spent on the lunar surface compared to the Apollo J-missions will provide an initial perspective on how the human body reacts to the lunar gravity environment. Deconvolving the response to multiple days in microgravity may necessitate measurements performed on the lunar surface in the crew cabin, however this would need to be fit into the as-of-yet undefined timeline of the mission while on the lunar surface. Detailed musculo-skeletal studies using model organisms requires use of non-human vertebrates, (e.g. mice and rats). Bone analog systems, such as tissue-on-a-chip and multi-physiological systems, can be used to study specific elements of bone. Since there are no data to understand actual lunar 1/6 ge alone or in combination with space radiation, short to long duration studies are scientifically relevant. Studies of muscle structure, function, and loss, may be conducted using the model organisms, *C. elegans*.

Goal 7d: Study the effects of lunar radiation on biological model systems—Understanding long duration exposure to the lunar radiation environment, alone and in combination with 1/6 ge, is an important objective for space biology research. However, the knowledge for early radiation impacts to biology, genetic and non-genetic, have never been characterized in the actual radiation environment of the Moon. Genetic and epigenetic studies, including other systems biology analyses, can be performed to obtain baseline data concerning the acute effects of space radiation on biological systems.

Goal 7e: Use biological model specimens to conduct single and multigenerational studies on the long term effects of the lunar environment and transportation to and from the Moon on biological processes—The use of the Artemis crew cabin to transport a biological experiment to and from the lunar surface may afford an initial view of how life forms respond this the lunar environment (or the crew cabin environment). However, addressing multigenerational processes may not be adequately resolved in a short surface stay. Nevertheless, many microbes replicate multiple times over the short duration of an early Artemis mission. Small, automated incubation systems (based on small satellite experiment design) enable culturing the microbes and conducting time course samplings and specimen preservation. Also, passive methods for culturing microbes may be used. These studies would mainly be focused on the radiation environment; however invertebrates, such as *D. melanogaster* and *C. elegans*, may be used to study combined radiation and lunar gravity effects. Although these studies would be short duration, the data would be important for guiding more long duration and complex investigation designs.

Goal 7f: Understand the effects/interactions of lunar gravity and the transitions between lunar gravity, microgravity, and Earth-normal gravity on reproduction and development, genetic stability, and aging—The study of invertebrates, such as *C. elegans*, may be used to address the effects of the gravity transition from 1 ge, to ~0 ge, to 1/6th ge, and back. Automated methods for preserving the specimens would need to be developed, if limited crew time for manual processing is not available, in order to capture the state of the organisms at time points post exposure to the change in gravity.

Goal 7g: Study the influence of the lunar environment and its effects on short- and long-term plant growth, productivity (as a food source), palatability, and nutrition—The opportunity to actually grow food within the crew compartment during Artemis III and taste-test such product will likely not be achievable. However, early missions may provide an opportunity to examine how taste changes in the lunar environment, and therefore provide initial supporting data for future long-term experiments. Sustainability of long duration missions and habitation on the Moon may include crop plant production to supplement food and nutrition. Studies may be conducted where packets of seeds can be left on the lunar surface for later retrieval by future Artemis missions to investigate seed viability and ability to germinate and result in normal plant production and nutrition. Also, studies examining early events in seed germination using *A. thaliana* may be possible depending on the hardware development time. The data from *A. thaliana* would provide insight into potential effects of partial gravity on the germination process, gravisensing, and other tropic responses.

Goal 7h: Evaluate the use and effectiveness of model plants in ecological life support systems—As with the goals described above that address biology and ecology experiments conducted on the lunar surface, there may not be sufficient time to directly grow and harvest plants during the Artemis III surface mission. Therefore, precursor measurements or data need to be identified and collected during Artemis III so that future, longer duration missions, may begin to adequately address this goal.

Goal 7i: Study the effect on microbes of long-duration exposure to the lunar environment— and **Goal 7j: Assess the effect on plants of long-duration exposure to the lunar environment—**Artemis III will provide raw material, in the form of lunar dust and regolith, to enable the investigation of how microbes and plants respond to the lunar environment. Specifically, the science questions associated with these goals, “Study the effect of regolith on microbial systems with respect to toxicity and nutrient availability”, “Assess metabolic changes affecting bioprocessing potential, virulence, and sensitivity to anti-microbials,” and “Study the use of regolith as a growth medium for plants” are enabled by access and collection of south polar regolith by way of studies performed on the Earth using such regolith samples, perhaps even regolith samples specifically collected and stored for use in future biologic studies, provided the collection of such samples does not negatively impact crew operations.

Goal 7k: Understand lunar dust behavior, particularly dust dynamics— and **Goal 7l: Understand lunar electrodynamics—**These goals are fundamentally enabled by the exploration of the lunar south pole. With the nearly constant movement of the lunar terminator in the south pole region, there exists a dynamic between illuminated, un-illuminated, and permanently shadowed regions that can begin to be understood during Artemis III. In the polar regions, solar wind plasma is flowing quasi-horizontally over the lunar surface. Current predictive modeling suggests that local topography (massifs, ridges, and craters) become obstacles in this plasma flow - with trailing mini-wakes or plasma voids forming immediately downstream of mountains and within polar craters. The surface potential in these shadowed wake regions is predicted to become strongly negative as the plasma expands into the void. Due to the lack of plasma flux in these plasma voids, tribo-charging human systems roving over the regolith in such regions will have increased electrical dissipation times possibly leading to a charge build-up. Models suggest that within larger polar craters, rover tires may become charged to thousands of volts negative and drill systems could charge quickly to hundreds of thousands of volts negative due to the fast accumulation of regolith-object tribo-charge and greatly reduced plasma dissipation (Jackson et al., 2015). The plasma is needed to offset the charge build-up and bring the systems into equilibrium – but in plasma-starved regions, there are not enough environmental currents to offset the charge build-up. Further, these tribo-charging interactions with the regolith will create grains that are hyper-charged as well. Even without human system operations, Surveyor imaging detected levitating grains forward scattering lights in regions just nightside of the terminator (e.g., Criswell, 1972), the observation strongly suggesting that the surface potential and plasma flow in these near-terminator regions are complex. The Apollo Lunar Surface Experiments Package (ALSEP) Suprathermal Ion Detector Experiment (SIDE) measurements found that the surface potential would go progressively stronger negative values as the terminator was approached. Thus, the interplay between plasma, regolith, dust and added human systems in the terminator region makes constraining the dusty-plasma environment an important part of understanding the evolution of the regolith, any possible movement of material, and the complex electrical environment that the astronauts will rove within. Understanding the dust and plasma environment has important implications for not only the natural environment, but also how it interacts with crew and equipment (Figure 5.7.1) and may impact those operations.

Figure 5.7.1: Apollo image AS17-134-20472. Apollo 17 astronaut Jack Schmitt at the lunar roving vehicle after his third EVA. Astronaut Schmitt's spacesuit became particularly dirty as he was eager to get near the surface to get close-up views of the samples he collected (Schmitt, personal communication, and https://apolloinrealtime.org/17/?t=144:51:01)

Constraining dust and plasma processes will require the emplacement of new, modern instruments to target plasma voids, dust transport, and dust adhesion, some of which will need to operate after the crew departs the surface. A passive system to sample plasma and dust, perhaps exposed only when crew is not performing an EVA, or in some way to measure the natural dust movement not induced by crew movement, may begin to offer insight into the magnitude of these predicted plasma voids and dust transportation (on a short timescale). Examining human system charging and space suit dissipation would also reveal the effectiveness of the natural plasma environment to remediate charge build-up. Given that Artemis III will be on the surface for ~20% of a lunar day, it will be critical for long duration experiments to fill in the full picture of the dynamics of dust and the plasma environment – especially as the region goes into shadow and crosses the terminator.

Investigation 7k-1: Understand the properties of electrostatic lofting and levitation—As described above, the Surveyor horizon glow observation suggests that the plasma dynamics, surface charge and dust transport immediately nightside of the terminator is complex. The interaction of the lunar surface with the space environment causes the regolith to become electrically charged, resulting in the transport of dust grains having sizes a few microns and smaller. Observations during the Apollo era of "horizon glow" and "streamers" above the surface are believed caused by charged dust grains ejected from the regolith.

Two modes of charged dust transport identified, levitation (Sickafoose et al., 2002) which operates on micron scale dust within about 10 cm of the surface, and lofting (Stubbs et al., 2006) in which ~0.1 micrometer dust grains may be transported to altitudes >100 km. Dust levitation occurs when the electrostatic forces balance the gravitational force while lofting occurs when electrostatic forces provide an impulse to the dust grain after it detaches from the surface. Apollo era observations, coupled with modern models, and lab studies have been used to try to untangle the complex dust dynamics driven by the plasma. A modern-day plasma and dust sensing system could be placed in the polar region to further refine our understanding of the dust transport.

Investigation 7k-2: Dust-Plasma Interaction on the Surface & Exosphere of the Moon—On the lunar surface, dust exposure to ultraviolet photons, solar wind plasma, and energetic particles is believed to cause dust charging and subsequent dust motion. For example, the Lunar Ejecta and Meteorites (LEAM) experiment, deployed during the Apollo 17 mission (Berg et al., 1976), detected what are believed to be highly charged dust grains moving at ~100 m/s that peak around the terminator regions where the potential transitions from positive to negative (e.g., Farrell et al., 2007), presumably accelerated by the complex electric fields in this region. Because the polar regions are always in the vicinity of the terminator, a polar mission like Artemis III is naturally suited to study this and similar phenomena.

In addition, due to micro-meteoroid bombardment, secondary particles typically smaller than a micron are launched from the lunar surface at speeds greater than 2.4 km/s forming a dust cloud around the Moon (Horanyi et al., 2020). LADEE's dust detector was able to directly measured these particles, whose density drops rapidly with distance from the surface. Characterizing the surface electric field and the electrostatically transported dust's grain size, charge, and spatial distribution is required to provide an understanding of the lunar dust-plasma environment and its impact.

Investigation 7l-1: Understand the plasma properties near the lunar surface and how they respond to external drivers, particularly across the terminator—There are significant synergies between this Investigation and Investigation 5b-1, investigating the near-lunar electromagnetic and plasma environment. To understand the drivers for potential hazards like differential charging, measurements are needed to better understand the response of the regolith to time variable inputs, how much flux the solar wind sputters, and what fraction of it is converted to higher energy (~1 keV) neutrals.

Investigation 7l-2: Understand the origin of lunar surface potentials, how they evolve between sunlit and shadowed regions, and under what circumstances they pose a threat to exploration— There are also significant synergies between this Investigation and Investigation 5b-1, investigating the near-lunar electromagnetic and plasma environment. Observations from Lunar Prospector indicate that nightside potentials can reach a few thousands of volts (negative), both during space weather events and during plasma sheet passages (Halekas et al., 2007, 2009). Surface potentials can be constrained via measurements of the DC electric and magnetic fields, as well as ion, electron, and energetic particle measurements to evaluate currents and charging.

Goal 7m: Monitor real-time environmental variables affecting safe operations, which includes monitoring for meteors, micrometeors, and other space debris that could potentially impact the lunar surface—Multiple environmental hazards can negatively impact the success of a landed mission. Existing operational procedures for known periodic events on the lunar surface should be developed and followed. To better prepare and design the research facilities for later Artemis capabilities, such as the foundation surface habitat, an important science objective for Artemis III is to make detailed measurements of the different components of the lunar surface environment, such as plasma, gravity, radiation, temperature, dust accumulation, and seismic activity, current impact flux and associated vibrations.

Investigation 7m-1: Establish a lunar environmental monitoring station to measure environmental variables such as temperature, vibration, dust collection, radiation, seismic activity, and gravity—The five plus years of data from the ALSEP instruments recorded the dynamics of the lunar environment and its interaction with the near-Earth space region and provided a baseline of knowledge of lunar seismic activity. Although the ALSEP stations were located on the central nearside, an Artemis III environmental monitoring station would initiate a new era of detailed study of the Moon and its interaction with the environment, provided it operates over a baseline long enough (~1 year) to measure small changes in the lunar environment, as well as allow for stabilization of sensitive measurements (e.g. heat flow). An environmental monitoring station extends science opportunities beyond the surface visit of the mission, and enables measurement of the effects of crew activity, liftoff, and subsequent crewed and robotic missions to be measured from the Artemis III site. The architecture of such a station, if flown on Artemis III, should be as simple to deploy as possible so as to not impact crew operations during EVA . These measurements also become a basis of understanding of the lunar environment that will be applied to planning future Artemis missions.

Investigation 7m-2: Provide real-time environmental information relevant to daily lunar operations—Operations on the lunar surface near the south pole during Artemis III will be in a new, dynamic environment. Understanding how crew movement and how any wheeled vehicle (if used) interacts with the local environment could inform future design to mitigate any negative effects of such interactions. In addition to a stationary environmental station, small electrical sensors placed on the astronauts suits, and/or near rover/cart wheels, could measure the tribo-charge build-up of the astronaut and rover/cart as they move over the regolith in various plasma regions. Dissipation times may be fast in sunlit regions due to photoelectron emission caused by UV illumination, so there would not be a large charge build-up. In shadowed areas, the plasma influx is reduced, leading to greater charge build-up on the astronaut’s boots and cart/rover tires. Small electrometers could be placed on these systems to measure this charge build-up over time. Modeling suggests that any wheel will continually develop tribo-charge as it rolls over the regolith. In low density plasma in shadow, the wheel cannot easily dissipate this charge, leading to anomalously large wheel potentials. An electrometer can thus be used to monitor this charge build-up. When the wheel stops roving, the dissipation of the charge can be used to derive the local plasma currents in the region.

SECTION 6

ARTEMIS III CANDIDATE SCIENCE PROGRAM

Artist's concept of geologic sampling at the Artemis III landing site. Samples and fieldwork performed by the Artemis III crew will redefine our understanding of the inner Solar System.
Credit: NASA

6. Artemis III Candidate Science Program

Based on the prioritized Investigations, the Science Definition Team built a notional, or candidate, program that would capture the highest-priority science for Artemis III and provide the greatest feed-forward to follow-on missions and leadup to the Artemis Base Camp. This candidate set of activities, taken together, work synergistically to address both the highest priorities and multiple additional Investigations. This program is meant to be used to provide planning teams a sense of the kinds of activities that are of the highest interest to the science community. It is expected that a more detailed science plan will need to be created when the exact landing site, HLS capabilities, and other details come into sharper focus.

Activities related to sample collection and return, *in situ* and field science, and deployed experiments are needed for a well-balanced program. This set of activities is not entirely dissimilar from the Apollo missions, and for good reason: the Apollo experience was refined over multiple missions via careful planning by a community of scientists to enable unparalleled science return from a well-trained crew. This means that some aspects, like the tools, EVA planning, etc., can be adopted from their Apollo predecessors. However, several important updates are enabled in the next generation of planning, particularly in the development of *in situ* science enabled by handheld instruments and in the treatment of samples responding to the community's updated understanding of volatile elements, as well as massive improvements in communications and geospatial information systems since the late 1960s.

The team needed to approximate how to fit these activities into the envelope provided by Artemis III planning. We therefore took the following guidelines from the HLS Solicitation:

- The HLS shall deliver, at a minimum, 100 kg of scientific payload to the lunar surface. Of this, 20 kg are allocated for the sample return containers, 10-20 kg are allocated for cameras or other sensors to be used in the habitable environment, and 60-70 kg are allocated for tools and instruments to be used or deployed by astronauts on the surface (HLS, 2019).
- The HLS shall return a minimum of 35 kg (or a goal of 100 kg) of scientific payloads (e.g. samples, inclusive of tare) to lunar orbit for return to Earth (HLS, 2019). Tare is expected to consume 9 kg of the upmass allocation in the minimum case, and 20 kg in the goal case.
- The HLS shall be capable of operating on the lunar surface for a minimum of 6.5 Earth days (HLS, 2019).
- The HLS shall be capable of supporting at least two (threshold) and five (goal) surface EVA excursions per sortie. Nominal EVA excursion is 6 ± 2 hours; the lower end of that duration (4 hours) is the requirement for Artemis III (HLS, 2019).
- The xEVA suit supports a walk-back capability of 2 km (xEVA, 2020).

This section outlines a program of returned samples and measurements (from both deployed instruments and *in situ* instruments) to accomplish the prioritized Artemis III science investigations within this mass allocation.

The Science Definition Team recognizes that the exact details of the mass allocation, along with other salient features such as exact landing site, have not yet been determined, so the general program outlined here is intended to envelop only the kind of planning that needs to go forward. The team anticipates that the program will need to be further refined. In addition, the team also recognizes that additional capabilities such as long-lived power/communications and pre-deployed assets (see Section 7) may be enabling to fully realize the Goals outlined in this report.

6.1 Samples

Many high-priority Investigations that are likely to be enabled by Artemis III surface operations require the return to Earth of samples collected on the Moon. This includes cases where a measurement cannot be made *in situ*, as well as cases where the precision and/or accuracy possible using instrumentation on Earth are significantly superior to their *in situ* equivalents. A robust sampling program will also complement a field campaign to understand the geologic setting of the Artemis landing site and surrounding region. Much information is available from remote sensing, but we must document the geology on the ground with astronaut observations, photographs, samples, and experiments (i.e., field geology) to understand the geologic context of the collected samples from these regions and provide needed ground truth for remotely-sensed data.

Our experience with the Apollo sample return program indicates that sample return is an investment in the broader planetary science community that continually yields scientific dividends decade after decade. Artemis program sample returns, beginning with the Artemis III mission, will likewise drive scientific discoveries for generations by adding a unique set of samples to those collected during Apollo. The samples returned from the high latitude landing sites under consideration for Artemis III are sufficiently distant from the six Apollo landing sites that they will include a large number of lithologies that are completely different from those in the current collection. This may include materials from the far side of the Moon and/or the lunar mantle. The Artemis III landing site is also likely to be within reach of regolith that remote-sensing and/or modeling studies suggest will contain ice. Determining the presence, extent, and characteristics of volatiles frozen in the regolith is not only the focus of many Investigations highlighted in this report, but it is also critical for resource assessments aimed at the sustained habitation of the Moon.

We considered a representative set of sample types designed to encompass the samples that best satisfy the needs of the highest-priority Investigations. Such a collection would enable characterization of the unique geology of the landing site, provide a diverse lithologic suite, and work toward a comprehensive understanding of the volatile record.

6.1.1 Types of Samples

1: Contingency (bulk) sample—Following established procedures from the Apollo missions, the first sample collected by Artemis III should be a contingency regolith sample, collected in the immediate vicinity of the lander during the first EVA. This assures that a minimum amount of sample is obtained even if the mission is suddenly shortened due to unforeseen circumstances. The contingency sample can be used to determine critical aspects of the local geology, which is the foundation upon which the more detailed Investigations are built. The contingency sample can also be used to address many of the specific Investigations, with the caveat that these Investigations will naturally be limited in both scope and scale by the lack of sample volume and diversity. If feasible, the contingency sample should be transported to Earth in a sealed container to prevent volatile loss or contamination. A second contingency sample, collected a short distance from the landing site and likewise sealed, can be used in conjunction with the first contingency sample to better address Investigations related to regolith volatiles and propellant contamination, even if a second EVA does not occur.

2: Small clasts from regolith samples—Pebble-sized (cm-scale) clasts or "rocklets," have been shown in the Apollo samples to accurately represent the lithologic diversity present at the landing sites. Collecting large numbers of these small samples makes it more likely to include rare rock types, as compared to the same mass of cobble-sized hand samples. This population potentially includes samples not only from the south pole, but also from the far side of the Moon. Although they are individually quite small, each rocklet can still satisfy the requirements of multiple science investigations because of advanced sample preparation and analytical techniques, which are much improved since the Apollo era. Use of a rake, or a scoop and sieve, can be efficient means of collecting a large number of small clasts from the regolith. The specific high-priority Investigations addressed by small-clast regolith samples include 1a-1, 1a-2, 1a-3, 1b-1,1b-2, 1b-3, 3a-1, 3b-1, and 3c-1, as well as other petrologic and geochemical studies that are of great importance to the science community.

3: Large samples—Collection of approximately decimeter-sized samples (called "hand samples" in Apollo parlance) consists of not only the retrieval of individual regolith fragments on the surface, but also pieces removed from even larger meter-scale boulders. Advantages of larger-scale rock samples, such as breccias, include the presence of textures, fabrics and other geologic relationships that provide additional context missing from individual clasts, such as formation history. Large samples also permit a greater mass of the same sample to be shared with the scientific community, resulting in a greater number of scientists having access to lunar materials, including those in the international community. The acquisition of larger rock samples represents a smaller investment of EVA time for a given mass than does the collection of rocklets. However, this increase in efficiency comes at the cost of a reduced opportunity to thoroughly sample the lithologic diversity of a given region. Because fewer large samples can be returned for any given total mass, it is preferable that astronauts perform preliminary analyses using *in situ* instrumentation to select specific rocks with the highest perceived scientific value. This can be done in conjunction with scientists on Earth in (nearly) real-time. Large samples can be used to address Investigations 1a-1, 1a-2, 1a-3, 1b-1,1b-2, 1b-3, 3a-1, 3b-1, and 3c-1.

4: Sealed core samples—Regolith composition and structure vary in three dimensions, preserving a record that generally increases in age with increasing depth below the surface. A core sample is an efficient and effective manner of sampling regolith at depth and can preserve stratigraphic and structural information. In order to minimize volatile loss and contamination, as well as the chemical and mineralogical changes that result from the exposure of lunar materials with the Earth's atmosphere, these samples should be sealed on the surface of the Moon, and should remain sealed until they are opened for preliminary examination by NASA's Astromaterials Acquisition and Curation Office. Sealed core samples are ideal for addressing Investigations 1f-1, 2a-6, 2b-1, 2c-1, 2c-3, and can also contain cm-scale clasts that can be used to address the same Investigations as the small and large clast regolith samples. If feasible, sealed core samples should also remain frozen to preserve variations in volatile content and or chemistry within individual core sections.

There are two proven methods for obtaining core samples in lunar regolith: Drill stems and drive tubes. Mechanized drill coring produces cores up to 2.5 m depth with drilling times that can be as short as 30 minutes. However, cores produced by drilling typically experience structural modification from the drilling process, which can compromise investigations that require preservation of textural and/or stratigraphic information. Core samples taken at high latitudes may also have frozen volatiles that are modified or lost due to the frictional heating that is a likely consequence of a faster coring rate. Given that deeper cores (1+ m) will typically represent samples with increasing age which are of scientific interest, and that there is no practical alternative method to reach such depths, the trade-offs that come with mechanized coring are unavoidable and must be accounted for during sample analysis.

Unlike motorized drill-core samples, astronaut-driven double drive tube cores are limited to ~70 cm depth. Drive tube cores have the advantage over their mechanized siblings in that they better preserve the stratigraphic and textural record within the core. This is important for studies of regolith formation, space weathering, volatiles, and impact processes. The length of a double drive core is also similar to the ~1 m penetration depth of neutron-based remote-sensing water detection methods, facilitating a comparison between the global mapping and the ground-truth provided by sampling.

A thorough sampling program is likely to be composed of both drill- and drive-cores, with the former used to explore the geologic record over a longer time frame, especially in locations where such data can be used to test model predictions of volatile retention and storage in areas with different sun exposure. Shallower cores are used to obtain regolith sections with the least structural and chemical modification possible, and also to explore lateral variations in near-surface volatile abundances in more detail.

5: Sealed surface (bulk) sample—In and around PSRs and micro-cold traps, it is predicted that there will be volatiles in the near-surface regolith, and potentially ice (“frost”) deposits on the surface. There is also the potential to collect regolith that has been contaminated by the exhaust of the descending lander, spacesuit degassing, or other anthropogenic sources, all of which are potentially important for both studies of lunar volatiles and studies of human-induced changes to the lunar surface.

In situ measurements of volatiles are clearly part of a rigorous campaign to characterize the volatiles on or near the surface in the Artemis III landing area. However, it is unlikely that the portable instruments available to the astronauts during Artemis III will be able to match the precision, accuracy, and limits of detection possible using equipment on Earth. The ideal scenario is a partnership between *in situ* measurements and samples collected for return to Earth, where there are a sufficient number of samples analyzed both on Earth and on the Moon to serve as a rigorous test of our ability to return a sample without modifying the chemical or isotopic information of the volatiles within as well as increasing the overall science return. Appropriate surface samples can be quickly and easily collected using a scoop, but in order to preserve the frozen volatiles for further analysis on Earth they should be contained separately in individually sealed containers. Keeping the samples frozen at temperatures as close to lunar ambient as possible would permit a greater preservation of the original chemical speciation of the volatiles as they were sampled. The full scientific potential of any ice-bearing sample of lunar regolith cannot be achieved until cryogenic sample transport and curation is possible (see Section 7.4). However, even room-temperature sealed samples can be used to determine elemental abundances and isotopic characteristics of the volatiles in the sample, once the complications arising from bringing the sample to room temperature are accounted for. A room-temperature sealed sample—despite its imperfections—can be used to address Investigations such as 2b-1 and 2c-1, and to inform science Investigations undertaken later in the Artemis program. A sample in a sealed container is likely to be several times more massive than the same sample in an unsealed sample bag due to the additional mass required for vacuum-sealed sample containment. The masses of the different containers are not known at this time, so it is difficult to predict how many sealed samples can be returned to Earth by Artemis III. However, it is clear that sealed samples are critical to successfully address all of the Investigations detailed in this report, especially those related to surface volatiles.

6: Undisturbed regolith surface sample—The surface of the Moon contains a delicate record of surface processes critical for a variety of studies, including space weathering processes that apply to many airless bodies in the Solar System. This record consists of not only the chemistry of the materials on the surface, but also the mineralogy and the microstructures preserved within those materials. As this uppermost portion of the lunar geological record is susceptible to both chemical and physical alteration, collecting undisturbed regolith without inflicting irreversible and irreconcilable damage requires special sampling, transport and curation considerations. The Apollo 16 tool kit included the Contact Soil Sampling Device (CSSD) which was specifically designed to sample the uppermost layer of regolith. If Artemis III astronauts are to return any undisturbed regolith samples from the Moon, a CSSD-like tool will be required. Decades of advances in materials research should provide modern alternatives to the beta cloth or velvet pads used in Apollo 16 CSSDs, with improved sample adhesion and decreased contamination. These samples would enable investigations such as 1f-1 as well as 2b-1 and 2c-1, assuming that CSSD samples can be returned vacuum-sealed to prevent loss of volatiles.

6.1.2 Sample Mass

The candidate sample program described here (Table 2) would include 4 rake samples (1.2 kg each) and 15 larger samples (1.05 kg each). Investigations focused on volatiles are best addressed by the collection of core samples of varying depths, from multiple locations chosen for different lighting conditions and therefore different volatile retention (8 cores proposed, with masses ranging from 1.5-4.5 kg depending on length). This would be supplemented by scoop samples of surface material, which serve to cover the study area in greater detail than can be attained by coring (20 samples, ≤ 1.2 kg each, plus 2 contingency samples). An updated version of the CSSD would be used to collect 4 samples of the regolith surface. This collection would total 85 kg of samples (Table 2), slightly more than the 64 kg average sample return mass from the Apollo missions.

Sample	**Type**	**Mass$_i$ (kg)**	**N**	**Mass (kg)**	**N$_{min}$**	**Mass$_{min}$ (kg)**	**Investigations**
Contingency	bulk	1	2	2	1	1	
Small clast	rake	1	4	4	1	1	1a-1, 1a-2, 1a-3, 1b-1 ,1b-2, 1b-3
Large clast	hand	1	15	15	4	4	1a-1, 1a-2, 1a-3, 1b-1 ,1b-2, 1b-3
Sealed core	drill	4.5	8	36	4	18	1f-1, 2a-6, 2b-1, 2c-1, 2c-3
Sealed surface	bulk	1	20	24	0	0	2b-1, 2c-1
Regolith surface	CSSD	0.5	4	2	2	1	1f-1, 2b-1, 2c-1
				Total 79		**Total 25**	

Table 2: Sample masses itemized by sample type, for two candidate programs, listed with the investigations that they would enable. Column labeled Mass$_i$ is the approximate mass per sample for each sample type. N and N$_{min}$ are the number of samples for the nominal and minimum sampling programs, with Mass and Mass$_{min}$ listing the corresponding mass for N or N$_{min}$ samples of each type.

It is of course possible to construct a less ambitious and less complete sampling program that results in less material being returned to Earth. However, it is not possible to construct such a program that accomplishes even a small subset of important Goals that are highlighted in this document, much less the many other worthy Goals and Investigations that depend on the return of appropriate samples. As an example, a smaller, less-comprehensive sample suite totaling 25 kg (Table 2) would enable a much smaller set of investigations to proceed, and many of those would be limited to serving as preliminary investigations. As the Artemis mass constraints and specific site selection bring the science objectives into better focus, the relative proportions of different sample types for return to Earth may be traded, but clearly, sample return mass should be maximized for Artemis III and subsequent missions.

All sample collection is built on the foundation provided by knowledge of the general geology of the region. This begins with remote sensing but is largely provided by astronauts who make critical observations of the samples in their geologic context. Wherever possible, synergies between sample collection and *in situ* measurements are leveraged for scientific gain, both on the Moon and after samples are returned to Earth. Similarly, samples collected by astronauts in the field will provide new and important ground truth for remotely sensed orbital data. These synergies are discussed in the following section.

6.1.3 Additional Considerations

Sample collection: A substantial advantage to crew collecting samples (over robotic sampling) is the greatly enhanced context that human crew can provide in the understanding of the sample setting. Astronauts must be well trained in geology and integrated into the science mission planning teams in order to understand the rationale for sampling stops, sampling requirements, and traverse plans. This will enable the astronauts to most effectively explore, recognize, and sample essential and unique elements of a field site, and to identify serendipitous sampling opportunities (LPI, 2007).

Apollo-era sampling tools (hammers, scoops, tongs, rakes, drills, drive tubes) and sample containers, storage, and curation tools were made almost entirely of Teflon, aluminum, and stainless steel. Overall, those materials were well-suited to the study of lunar materials (Day et al., 2018). If new materials are under consideration for use in Artemis sampling tools, careful consultation with the CAPTEM Lunar Science Subcommittee is advised to aid in the vetting of new materials. In addition to these tools, extensive surface documentation (voice description, field context, camera documentation, etc.) is a critical component of sampling and other surface science activities.

Contamination Knowledge: Contamination knowledge (CK) is the information gained from studying the collected/curated reference materials and witness plates in conjunction with returned sample analysis (Harington et al., 2018). Establishing a robust CK for Artemis is of paramount importance to prevent science loss due to contamination of returned samples during sample collection, return, storage, and curatorial processing. Artemis tools should be tested against different targets (rocks, soils, ices) so that loss and transfer of material to and from tools is accounted for. A series of modelling and experimental trials should be performed that can verify contamination performance for different analytical techniques. Tools should be tested using well characterized analogs of rocks, soil, and volatile-rich samples expected at the Artemis landing site(s). The chemistry and isotopic composition of such analog materials should be determined using a range of analytical techniques to quantify contamination potential. The Apollo-era tools should be used as witnesses of contamination during lunar sampling, e.g., Pb contamination was an issue during Apollo (Nunes et al., 1974) and there is potential for metal transfer (Day et al., 2018) . Furthermore, chemical and isotopic determination of any potential tool or container coatings and materials will be critically important to understand contamination risk to returned samples. Analysis of witness plate materials and spacecraft components (including sealants, fuels, bags, suits, etc.) is critical to evaluate potential organic contamination (Elsila et al., 2020). Equally important is to evaluate how tools and sample bags change under different sterilization methods and/or radiation environments and their effects on sample contamination. Assessing the contamination from landing equipment and descent engine exhaust is critical for understanding and interpreting endogenic vs. exogenic organic/volatile-bearing samples. Such measurements would also be relevant to the collection of material from the lunar exosphere.

Volatile Containment: The collection of volatile-rich polar regolith using different sampling techniques must be assessed to mitigate science loss (e.g., ice sublimation, volatile release, fractionating isotopic ratios, breakdown of organic molecules, mineral reactions, etc.). Further, it is important to assess how various storage containers will allow preservation of volatiles, ices, organics, and gases, as well as the effect that the preservation of volatiles has on the ability of the samples to be used for other geologic analyses. It will be important to simultaneously collect *in situ* measurements on the lunar surface as volatile-rich samples are being collected in order to characterize volatile loss to the lunar environment and to understand the degree of modification of the sample once it is collected, stored, and curated. Understanding sample integrity (the original state) from collection through transportation and storage to analysis is critical to maximize the scientific return of these precious samples. Without this protection, sample properties and compositions could change, ultimately influencing the interpretation and understanding of a given sample and, by extension, the Moon. This is especially critical for the safe sampling, transportation, storage, and analysis of volatile-rich samples (Mitchell et al., 2020).

Curation and Analysis: NASA has more than fifty years of experience in curating, processing, and distributing astromaterials, as well as providing fair and open access to these samples to the international science community. A similarly fair, open, and impartial sample request and allocation system, to which all other NASA sample collections adhere to, is recommended for the Artemis samples, and could follow the well-established existing CAPTEM model and NASA sample loan scheme. In addition, the Apollo program anticipated the advancement of analytical techniques and prepared for this by sealing a subset of lunar samples for future investigations under a variety of conditions (see Stroud et al., 2020). Recently, the ANGSA (Apollo Next Generation Sample Analysis) program has begun to fulfill that task (NASA, 2019). Artemis may consider a similar approach.

Next-generation laboratory analysis: The capabilities of modern planetary science instruments far exceed those of their Apollo-era counterparts. However, it is widely recognized that investments in laboratories have not kept pace with those advances (NAS, 2019), and that this lack of investment in state-of-the-art equipment reduces the scientific yield of extraterrestrial samples such as those that will be collected by Artemis III. An additional consequence of relying on an aging laboratory infrastructure is that older instruments typically require greater sample mass per measurement, as compared to their modern equivalents. Greater sample consumption effectively reduces the overall scientific yield of the samples and the mission. A targeted investment is therefore required to address aging instrumentation. Sample analysis capabilities for extraterrestrial samples are also limited by a shrinking scientific workforce at many universities and NASA centers, as well as limited opportunities for the training of next-generation scientists (NAS, 2019). Finally, state-of-the-art measurements are only possible when state-of-the-art curation techniques are employed, and the development of such techniques also requires a targeted investment strategy.

6.1.4 Findings and Recommendations

Finding 6.1.4-1: The optimal sample return program is built upon geologic context observations made by well-trained astronauts, aided by modern tools and real-time communication with scientists on Earth.

> **Recommendation 6.1.4-1:** Astronauts should participate in an Apollo-style course in geology and planetary science in order to provide optimal *in situ* geologic characterization of lunar sample collection sites. A dedicated team of scientists should serve in an Earth-based Artemis III Science Mission Center with real-time two-way audio and one-way video between the crew and the Science Mission Center.

Finding 6.1.4-2: The high-priority Investigations described in this report require the collection of a diverse set of sample types, collected from geographically diverse locations broadly representative of the complex geology of the south polar region, and a total return sample mass from the Artemis III south polar site exceeding the average return mass for the Apollo missions.

> **Recommendation 6.1.4-2:** Astronauts should be trained and equipped to collect a variety of surface and sub-surface samples. NASA should plan to return total sample masses in excess of previous lunar sample return missions.

Finding 6.1.4-3: Sample collection and *in situ* measurement campaigns are complementary and increase science return.

> **Recommendation 6.1.4-3:** NASA should ensure that sample collection and *in situ* measurements are carefully choreographed to maximize science return. Examples of such coordination include the characterization of rock samples with *in situ* instrumentation to aid in prioritization of samples selected for Earth return, and *in situ* volatile measurements made in conjunction with sample collection to characterize volatile losses from sample collection, transport, and/or curation, and efforts to provide “ground truth” for orbital remote sensing datasets.

Finding 6.1.4-4: The return of hermetically sealed volatile bearing samples from the lunar south polar region can preserve lunar volatile signatures within the sample containment system and prevent gas-exposure hazards in the crew cabin.

> **Recommendation 6.1.4-4:** NASA should focus on the development of lightweight, double-sealed vacuum containers to return volatile bearing lunar samples to Earth. Minimizing the mass penalty for vacuum-sealing any given sample results in increased scientific yield of the mission since more mass can be allocated to the lunar samples instead of the sampling hardware.

6.2 Deployed Experiments

Deployed experiments consist of autonomous instrument packages installed on the lunar surface, either robotically (for measurements before human surface activity), or by astronauts during

EVA. Such “suitcase science” packages enable a variety of geophysical and environmental investigations. NASA last allocated specific planning funds to this type of effort in 2009 under the Lunar Sortie Science Opportunities (LSSO) program, though since then, efforts to mature instruments for the lunar surface (to be deployed robotically) have been undertaken via NASA Planetary Science Division programs like PICASSO, MATISSE, DALI, and the Lunar Discovery and Exploration Program (LDEP) program elements soliciting payloads as CLPS manifests (NPLP, LSITP, PRISM).

- PICASSO: Planetary Instrument Concepts for the Advancement of Solar System Observations
- MATISSE: Maturation of Instruments for Solar System Exploration
- DALI: Development and Advancement of Lunar Instrumentation
- NPLP: NASA Provided Lunar Payloads
- LSITP: Lunar Surface Instrument and Technology Payloads
- PRISM: Payloads and Research Investigations on the Surface of the Moon

Some measurements, in addition to their high science value, have the ancillary benefit of increasing astronaut safety and reducing risk. Among possible deployed experiments, this applies in particular to environmental measurements. An environmental package deployed before astronauts arrive would provide valuable information about the working environment (e.g., light/dark, shadows, temperatures, radiation) which can be used to characterize the landing site and inform operations. Such data would likely also influence the design of some of the follow-on Artemis Base Camp infrastructure.

Sensitivity is also important. If people working in the area are too disruptive, it could adversely affect some measurements. For example, astronauts working in areas of near-surface volatile concentrations could mechanically disturb them just by walking, which creates thermal disturbances that alter the natural state and distribution of volatiles. The presence of astronauts could also contribute to endemic surface volatile deposits through spacesuit degassing. No *in situ* measurement can be made without some measure of disturbance, but environmental monitoring payloads may be good candidates for early robotic deployment, assuming such negative factors can be reduced and/or mitigated.

Experiments requiring more complex deployments, by comparison, argue for human intervention. Geophysical instruments tend to require more interaction, such as precise siting, alignment, and strong coupling with the surface/subsurface, which are better achieved and easier to troubleshoot in real time by crew. Heat flow experiments in particular have been shown to pose challenges robotically (e.g. Mars InSight). Similarly, some environmental measurements are best achieved with the ability to choose very specific deployment locations (e.g., deploying a sensor in a cm-size micro cold trap).

6.2.1 Geophysical Monitoring

Long-lived, networked geophysical observations from the surface of the Moon have consistently remained a high priority among the lunar community, and could include the following measurements:

Geodetic monitoring (Investigation 1a-3): Geodetic monitoring is accomplished via laser ranging to passive retroreflector arrays. Active radio beacons for interferometry can complement the laser ranging technique. NASA has already identified retroflector payloads for missions being flown under the umbrella of LDEP. Modern retroreflectors are smaller and lighter than those deployed during Apollo, require no power to operate, and will last for decades post-deployment. Similar payloads should be considered for Artemis surface missions to accomplish a variety of key science objectives relating to fundamental physics and geodetic control, among others. A retroreflector at the South Pole would greatly expand the footprint of the existing array, improving constraints on several geodetic parameters directly relevant to internal structure determination.

Heat flow (Investigation 1a-3; 1b-2; 2c-2): Heat flow investigations are accomplished by measuring thermal properties in the shallow subsurface, typically by drilling a borehole, as was done during Apollo, although modern deployment mechanisms that use jets of compressed gas to loft regolith out of the hole are also being developed under LDEP. Heat flow measurements could also feasibly be taken down the hole left behind by the collection of core samples, although there is a trade-off between the depth of the hole and the length of the experiment required to average out thermal cycles. At the poles, thermal stability on the diurnal timescale is achieved beneath only ~20 cm of regolith. Core tubes sample to ~70 cm, but at that depth there is an approximate +/-10K annual temperature cycle (Martinez et al., 2020), which would require at least a year of observation to average out.

All of the Apollo heat flow experiments exhibited aperiodic temperature rises characterized by decreasing magnitude and increasing time delay before onset at greater depths. These transients were likely initiated during experiment emplacement when astronaut activity disrupted the thermal and radiative properties of the surrounding regolith (Langseth et al., 1976). Care must be taken to ensure such disturbances in the vicinity of a potential heat flow experiment are minimized during Artemis III.

Thermal measurements of the surface and subsurface are also of high priority to support Objective 2 Investigations pertaining to lunar polar volatiles (particularly Investigation 2c-2). Thermal characterizations are required to place the detection of volatiles in context as different volatile components have varying sequestration temperatures where the volatiles are expected to be stable over geologic time. Thermal measurements also provide ground truth critical for addressing the extent to which the predicted distribution of ice corresponds to the measured vertical and horizontal ice distributions. Such correlations allow for the refinement and verification of predictive models pertaining to volatile distributions in varying geographic locations.

Electromagnetic properties (Investigation 1a-3; 1b-2; synergies with Investigations 5b-1, 7m-1, 7m-2, 7k-1, 7k-2, 7l-1, 7l-2): Electromagnetic properties (e.g. electric and magnetic field strength/direction; electrical conductivity) can be captured via electromagnetic sounding of the Moon using its passage through Earth's magnetosphere, either with independent surface measurements, or those taken in tandem with orbital measurements. Particle measurements can complement electromagnetic field measurements by quantifying plasma effects that limit the minimum interrogation depth, with the additional benefit of characterizing the spatiotemporal processes that influence volatile transport, surface weathering, and surface charging.

Seismic properties (Investigation 1a-3; synergies with Investigations 3b-1, 7m-1, 7m-2): Short-lived, single station seismic deployments can only partially address goals related to the structure and evolution of the lunar interior. Passive seismic experiments ideally require longevity in order to record sufficient seismicity for structure determination, although a short-lived experiment may be useful for assessing the seismic noise floor, as well as for constraining seismic hazard at the

South Pole. Active seismic experiments, either using an astronaut-deployed source, or via the intentional impact of expended spacecraft parts (both done during Apollo), are another option, but both passive and active single-station deployments primarily address regional, one-dimensional, or shallow structure. Long-lived, globally distributed geophysical observing stations are needed to fully interrogate the Moon's three-dimensional structure, including the deepest interior.

6.2.2 Environmental Monitoring

The Moon's atmosphere, termed a "surface boundary exosphere" (SBE), is thin and extends all the way down to the surface boundary. Other solar system bodies with SBEs include planet Mercury and the satellites Europa, Ganymede, Callisto and Enceladus. SBEs are the least understood type of atmosphere in the Solar System and the lunar atmosphere is the only SBE atmosphere in the solar system that is sufficiently accessible that researchers can expect to study it in detail. Measurements that capture physio-chemical processes, including sputtering, can contribute to our understanding of the formation and dynamics of such exospheres, and how they influence dust-plasma dynamics.

Environmental monitoring captures exosphere measurements relevant to both the character and origin of lunar polar volatiles as well as assessment and mitigation of exploration risks. All measurements related to electrodynamics and dust fall broadly under Investigation 7m-1, and include:

- Ion & electron distribution (temperature/velocity/density/suprathermal tails) to monitor the interaction of solar wind with the lunar surface (Investigation 7m-2, 7k-1, 7k-2, 7l-2)
- Energetic particle observations (Investigation 7k-1, 7k-2, 7l-2)
- Energetic neutral atom observations (Investigation 7l-1)
- Investigate species in the exosphere (synergy with Investigation 2c-3)
- DC and AC magnetic and electric field strength, direction, & variability (Investigation 7k-1, 7k-2, 7l-1, 7l-2)
- Dust size distribution, density, charge state, and the vector direction and magnitude/velocity of the convective flow of dust (Investigation 7k-1, 7k-2)

Observations from the surface can be coordinated with measurements from orbit to reveal connections between processes on different scales.

Measurements related to volatiles include:

- Surface frost monitoring (diurnal and seasonal) (Investigation 2a-3)
- Surface and subsurface temperature (diurnal and seasonal) (Investigation 2c-2)
- Volatile species on the lunar surface and in the exosphere over time; both disturbed and exposed surfaces in both PSRs and in transient light (volatile migration) (Investigation 2c-3)

Measurements related to other environmental factors include:

- Monitoring of natural impacts (primary impacts, impact ejecta) and debris entrained by rocket plumes
- Seismic hazard and risk assessment
- Mechanical witness plate to investigate long-term deep space exposure and dust adhesion

Note that monitoring of meteoroid impacts (which can release and mobilize volatiles) and the solar wind simultaneously with monitoring of volatile migration is valuable to place constraints on the overall volatile migration processes.

6.2.3 Understanding the human impact on the Moon

During the controlled descent of landers on the Moon, rocket exhaust disturbs the lunar surface, and can deposit volatile species that interfere with investigations of the Moon's unaltered chemistry. The movement of astronauts on the surface can cause build up of electrostatic discharge on their suits, which can similarly interfere with sensitive environmental monitoring. Investigations to specifically address human-induced changes and environment-induced hazards include:

- Investigate species in the exosphere and on the surface (Investigation 2f-1)
- Suit charge monitoring (Investigation 7m-2)
- Characterize resultant surface contamination from HLS landing plume/landing effects and astronaut suit degassing (Investigation 2f-1)

6.2.4 Findings and Recommendations

Finding 6.2.4-1: Geophysical and environmental monitoring are needed to address multiple Artemis III Objectives.

> **Recommendation 6.2.4-1a:** The Artemis III mission is an opportunity lost if the first of a series of geophysical and environmental network nodes is not deployed. Although incremental science can be obtained with short-lived experiments, long-lived power and communication capability will be required to fully enable prioritized investigations (see Section 7.1). The Artemis III node can be augmented by both robotic and human future missions, building towards a global network.
>
> **Recommendation 6.2.4-1b:** Geodetic monitoring via Earth-based laser ranging requires no lunar surface power or communication to function and hence will provide science return even in the absence of such capabilities. We advocate for geodetic monitoring capability to be prioritized for Artemis III.

6.3 *In Situ* Experiments

Whereas deployed science payloads can provide long-lived platforms with which to obtain science data, and can either be pre-deployed prior to crew arrival and/or deployed and calibrated on the surface by crews, *in situ* science payloads are used during EVA to give astronauts increased scientific awareness of the exploration area in real time. This awareness helps with sample characterization both before and during sample collection, which is of utmost importance in a restricted return mass environment. *In situ* experiments can be used in a variety of ways, from an astronaut holding an instrument and acquiring data in their gloved hand, to instruments mounted on a tripod, tool cart, or mobile platform, to instruments deployed at a variety of EVA stations to monitor sampling or other science activities or image sample targets.

In evaluating the science objectives proposed for the Artemis III mission, several 'classes' of *in situ* measurements emerged, each with a different deployment style tied to these science objectives.

6.3.1 Sampling Instrumentation Suite

As discussed in Section 6.1, sampling is absolutely vital in answering outstanding lunar science questions. Careful selection and curation of these samples (Table 2) must be done to understand the geologic context under which the samples were taken and even to possibly triage samples for return to Earth should more sample mass be collected during the mission than can be returned, due to the HLS upmass availability. *In situ* instruments can be useful for sample triage, for providing data from a greater variety of lunar locations than can be sampled due to restricted upmass, and for providing the crew with greater awareness of the geologic context of an area real-time during an EVA.

Properly and thoroughly documenting a sample's context, both before and after sample collection, is critical to maximize the utility of that sample to scientists back on Earth in addressing the science Objectives discussed above. *In situ* imaging permits a wealth of context-generating observations, including a) documenting sample collection (pre- and post-collection), b) documenting geologic context throughout each EVA, c) documenting the deployment of any instrumentation (whether *in situ* or deployed), and d) sending photos back to ground control teams (either real-time during an EVA or following the conclusion of each EVA, whichever the communications architecture will support).

As seen in the science traceability matrix (STM) (Table 1), obtaining compositional information (geochemistry and/or mineralogy) is also critical to addressing Artemis III science Objectives. In the event that the HLS upmass capabilities are not sufficient to return enough samples to adequately address a particular Investigation, the ability of the crew to quickly obtain *in situ* geochemistry and/or mineralogy data may close the gap left by this restricted upmass. Additionally, should sample triage be required, these *in situ* data will aid both the crew and ground control teams in ensuring the most scientifically valuable samples be returned to Earth.

6.3.2 Volatile Monitoring

The study of volatiles through sample collection is critical in several Artemis III Investigations (Investigations 2a-1, 2a-2, 2a-3, 2a-4, 2a-5, 2a-6, 2a-7, 2b-3, 2c-1, 2d-3). It is important to understand the evolution of volatiles during the sampling process to ensure that no volatiles are lost, or, if volatile loss does occur, to characterize that loss in order to properly inform the subsequent analysis and interpretation of the returned sample. Relevant *in situ* measurements include elemental and molecular composition of volatiles as well as thermal mapping of regions sequestering volatiles and volatile sample sites. To that end, measurements taken during the sampling of any material suspected to contain volatiles are a high priority for all Investigations correlated with volatiles sample return. In addition to the required measurements during sample collection, *in situ* measurements taken independently to characterize the form, character, and distribution of volatiles in their endemic state on the Moon are also scientifically important.

6.3.3 *In Situ* Geophysical Payloads

In addition to the deployed geophysical payloads discussed above, Investigations 1b-2 and 1f-1 could also benefit from the mobile collection of data. As the Artemis III crew will be moving around the exploration zone, the acquisition of geophysical data via traverses and/or stationary measurements at sites selected for sampling can provide critical data about the subsurface structure of the exploration area. Measurements to characterize regolith structure and diversity and broad-scale geologic characterization would all be aided by the ability of the crew to deploy geophysical instrumentation en route from station to station, or at a variety of stations as needed.

6.3.4 Down-Hole Instrumentation

As seen in Section 6.1, samples taken using a drive tube are a high priority for Artemis III. These drive tube operations will leave behind a 'window' into the regolith through the hole left behind after the sample is extracted. Measurements to evaluate thermal stability and volatile evolution will help address key science investigations (Investigation 1b-2, 2c-2) and will capitalize on already prioritized crew activities, with the capture of drive tube samples. Other investigations may make opportunistic use of down-hole deployment as a more thermally stable environment than the surface, with better ground coupling (e.g. seismic measurements).

6.3.5 Geotechnical/Physical Characterization Instrumentation

Investigation 1f-1 to characterize regolith at a number of diverse locations (including shadowed and sunlit regions) is critical not only for science benefit but also to reducing risk for future Artemis missions. Trafficability of the regolith, as well as mining and construction activities, are affected by the geotechnical properties of the regolith, and can be assessed via *in situ* measurements to evaluate the bulk density and porosity, relative density, compressibility, shear strength, and permeability of the regolith. Many of these geotechnical properties are disturbed or altered when samples are collected and returned to Earth for study and analysis, hence the importance of *in situ* measurements.

6.3.6 Site Assessment

In addition to the observations addressed above, *in situ* measurements are valuable in overall site assessment in order to completely characterize a site, both real-time during exploration and to form a complete site picture post-mission, which is critical for placing future scientific discoveries in the broader mission context. All science payloads deployed during Artemis III will contribute to this large scale site characterization.

6.3.7 Findings and Recommendations

Finding 6.3.7-1: *In situ* instrumentation will be greatly beneficial in addressing a number of Artemis III science investigations, including instrumentation to support sampling, volatile monitoring, geophysics objectives, down hole monitoring, and geotechnical characterization.

> **Recommendation 6.3.7-1a:** NASA should ensure that *in situ* imaging capability is available to crews during EVA to document exploration, sampling, and instrument deployment.
>
> **Recommendation 6.3.7-1b:** We recommend NASA provides a mission capability of real-time transmission of data from *in situ* science instrumentation that provide documentation for site characteristics and enables a science support team (backroom, operations center, etc.) to support EVA operations with (near) real-time feedback to the crew when necessary on science decision-making, as well as provide processed data when necessary (i.e. helping convert raw data into tactical decision-making). This requires prior establishment of high

bandwidth communication that is capable of extensive real-time data transmission to accommodate use of valuable measurements from modern sensors.

6.4 Operational Considerations of both Deployed and *In Situ* Instrumentation

With the expected downmass capability of the HLS, careful consideration must be given to the complement of tools and instruments chosen to accompany the crew. After accounting for the mass that will be consumed by the sampling tools required to gather samples identified in Section 6.1, the remainder must be shared between deployed experiments (Section 6.2) and hand-held instruments to be used *in situ* (this section). Although all of the sampling activities and experiment classes discussed in the above sections are important to maximize science returned from the Artemis III missions, we also highlight the need for careful consideration of their operational implications.

Maximizing crew time during Artemis III will be of vital importance, and not detracting from crew efficiency in scientific exploration will be critical. Although *in situ* instrumentation will be valuable in addressing a number of high priority Investigations, crew time must also be protected to allow for exploration and sampling. Careful consideration and planning of the order of operations during EVA should maximize crew efficiency. Whereas the sampling instrumentation suite discussed in Section 6.3.1 is intended to be used in conjunction with most or all sampling locations, some *in situ* and deployed instruments must be timed at appropriate locations within operations at a single site, within a single EVA, or within a mission. For example, volatile monitoring payloads intended to capture time series data throughout the collection of a single sample must be placed intentionally within an EVA timeline. Depending on the payloads selected for flight, EVA timelines should reflect these considerations.

To collectively address the Objectives supported by both deployed and *in situ* experiments, measurement techniques are preferred that maximize science return by addressing multiple Investigations and have the ancillary benefit of increasing crew safety and/or reducing risk for future missions. If science payload downmass is limited, and/or pre-deployed assets are not available (Section 7), this necessitates further prioritization of measurement techniques (Table 3).

Measurement Technique	Primary Investigation(s)	Synergistic Investigations
1. *In Situ* Volatile Monitoring	2a-1, 2a-2, 2a-3, 2a-4, 2a-5, 2a-6, 2a-7, 2b-1, 2c-1, 2c-3, 2d-1, 2f-1	1a-1
2. Deployed Environmental Monitoring	7m-1, 7m-2, 7k-1, 7k-2, 7l-1, 7l-2, 5b-1	2a-3, 2a-7, 2c-3, 2f-1
3. Deployed Geophysics Instruments	1a-3, 1b-2, 2c-2	3b-1, 5b-1, 7m-1, 7m-2, 7k-1, 7k-2, 7l-1, 7l-2
4. *In Situ* Geochemistry/Mineralogy	1a-1, 1a-2, 1b-1, 1b-2, 1b-3, 1f-1	3a-1, 3b-1, 3c-1
5. *In Situ* Geotechnical Properties	1f-1	2c-2, 3c-1
6. *In Situ* Geophysics (Traverse Instrumentation)	1a-3, 1b-2	

Table 3: Prioritized list of measurement techniques capturing both deployed and *in situ* experiments.

Finding 6.4-1: Existing mass allocations expected to be available on the HLS system for delivery of tools and payloads to the lunar surface are insufficient to achieve the full spectrum of science objectives outlined by the stakeholder community.

Recommendation 6.4-1: NASA should solicit the development of instruments that are capable of addressing more than one measurement need and/or science Investigation.

6.5 Cross-Discipline Advances

The fundamental science Investigations and surface activities developed in this report will also be essential to achieving NASA goals across its mission directorates – SMD, HEOMD, and the Space Technology Mission Directorate (STMD).

As discussed in the Introduction (Section 2) understanding the resource potential of the Moon is a key part of the Artemis program. As described in NASA's Artemis Lunar Exploration Overview, developing *in situ* resource utilization technologies is the responsibility of the Space Technology Mission Directorate, and such activities are outside the scope of this SDT report. However, many of the Investigations which are part of the candidate program to be carried out on the Artemis III mission will provide important new information relevant to leveraging the Moon's resources towards a sustainable human presence on the surface:

- Identification of surface frost composition
- Identification of surface frost locations to enable mapping
- Determining the speciation of hydrogen
- Abundance of hydrogen across ice-stability depths.
- Distribution of surface hydrogen across scales of 1m to at least 1000m
- Establishing a lunar environmental monitoring station
- Determine the distribution of micro cold traps across the lunar surface within dominantly illuminated regions
- Understand the distribution of water/OH within a PSR
- Determine the geomorphology/stratigraphy of the regolith to a depth of 1m
- Determining geotechnical properties

When considered in the context of both existing and planned orbital datasets (e.g., LRO, Korea Pathfinder Lunar Orbiter (KPLO), Trailblazer) and planned surface missions (VIPER and individual LDEP polar landers), the samples collected and fieldwork performed by the Artemis III crew will provide new ground truth context for understanding the abundance and distribution of hydrogen and oxygen species useful for resource utilization at a previously unexplored location on the surface, facilitating an improved understanding of the grade and tonnage of the south polar resource deposits. Similarly, collecting new lunar regolith samples (such as drive cores) will provide new geotechnical information – parameters such as particle size distribution, specific gravity, bulk density, compressibility, bearing capacity – from the surface and accessible subsurface of the Moon in a previously unexplored location, helping to guide industrial processes and regolith extraction strategies.

The geotechnical information gleaned from the candidate scientific program, as well as the documentation on the surface carried out by the Astronauts, will also provide new reconnaissance information, such as the surface block size frequency distribution and validation of lighting condition models for the construction of the Artemis Base Camp.

Close cross-directorate coordination should be maintained between SMD, HEOMD, and STMD to ensure that results of the Artemis III mission can be fully leveraged by all of the stakeholders and applied to future Artemis missions and activities at the Artemis Base Camp.

Finding 6.5-1: In light of the importance of the Artemis III scientific results towards implementation of commercial resource extraction strategies and the construction of the Artemis Base Camp, efforts should be maintained to promote cross-directorate integration between the diverse stakeholders within NASA in HEOMD, SMD, and STMD, and in the external scientific, engineering, and commercial communities.

> **Recommendation 6.5-1a:** A standing working group comprising scientific leadership of the Artemis program in SMD should be established and closely coordinate with representatives of STMD and HEOMD to ensure clear lines of communication and facilitate program implementation.
>
> **Recommendation 6.5-1b:** NASA's existing Program Analysis Groups, such as LEAG and CAPTEM, serve an important community role synthesizing community input across diverse stakeholders in the engineering, science, and commercial communities, and should be leveraged as the program continues to promote external community engagement to the fullest practical extent.

All Artemis III mission activities will be of interest for the people of Earth, as the first human missions to another world in the 21st century. Communications and public engagement of Artemis missions will play a pivotal role in educating and inspiring the next generation of explorers, informing the public about the Moon, the space environment on the Moon, and the Solar System around us. Rich opportunities for public engagement will be enabled by cameras carried by the astronauts on the lunar surface to document the Artemis III mission.

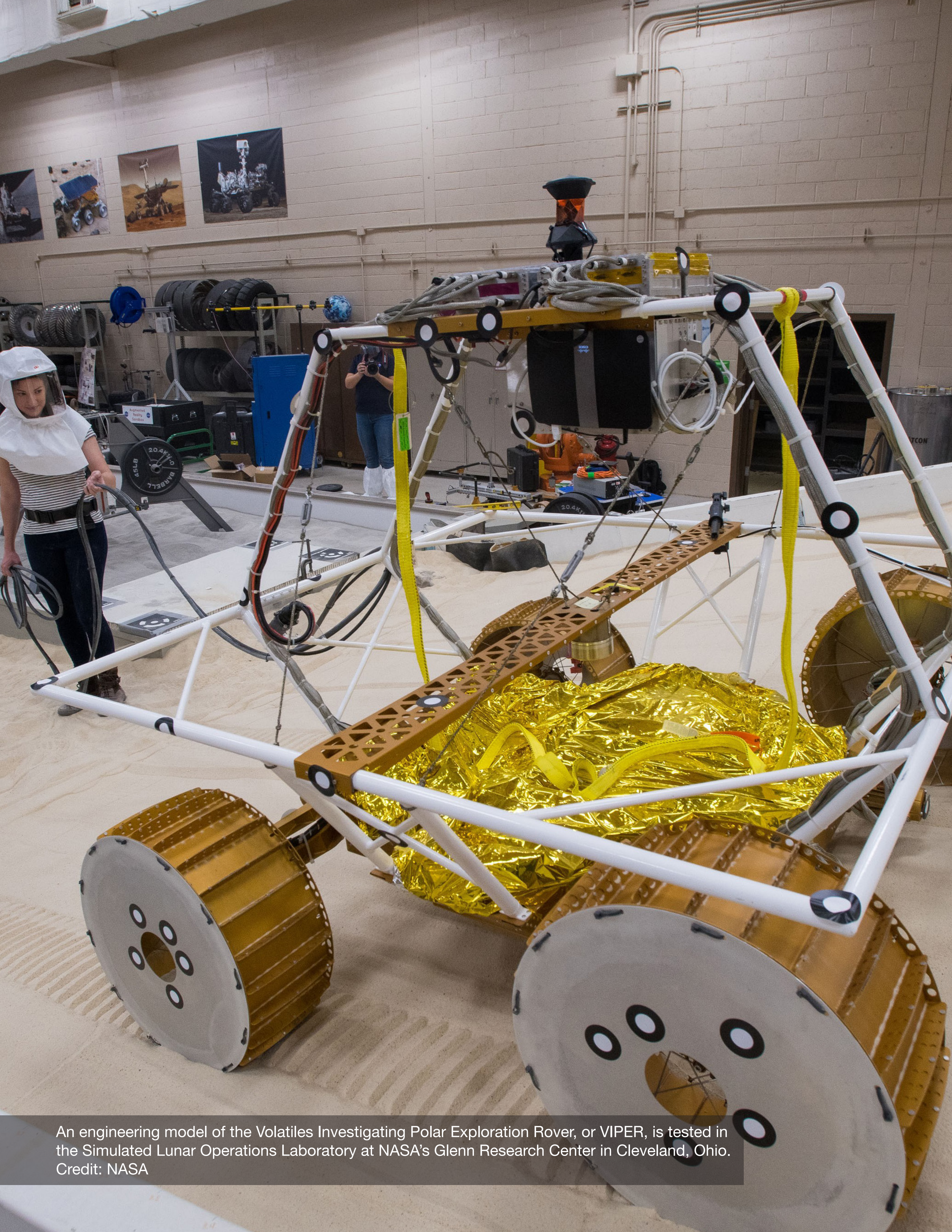
The transformational planetary science knowledge resulting from the Artemis III mission will also provide new discoveries that will be important for understanding the other planets in the inner Solar System, as well as small bodies:

- Understanding the properties of the lunar regolith in the polar regions will be relevant for studies of other airless bodies, such as Mercury and small bodies.
- Understanding the human impacts on the environment will be used to inform planetary protection requirements for human Mars missions.
- New samples with clear geologic context from the polar regions will improve the crater chronology already established for the Moon, and used as the basis for understanding the relative age stratigraphy of other inner solar system bodies, such as Mercury and Mars.
- Magma oceans have been identified as a common step in the formation and evolution of all of the inner planets. It is expected that samples collected on the Artemis III mission will include both mantle material and the primary crust, providing new constraints on the processes that created the Moon's magma ocean.

Almost equally important is the reality that Artemis III will be the first time human beings have conducted extraterrestrial field science on other worlds in five decades. Procedures and operations techniques, particularly for sample acquisition and curation, developed for the Artemis III mission will influence future Artemis missions, research activities and operations at the Artemis Base Camp, and future expeditions to Mars.

SECTION 7

ENABLING CAPABILITIES



An engineering model of the Volatiles Investigating Polar Exploration Rover, or VIPER, is tested in the Simulated Lunar Operations Laboratory at NASA's Glenn Research Center in Cleveland, Ohio.
Credit: NASA

7.0 Enabling Capabilities

During the course of its deliberations, the SDT identified several capabilities that were considered to be enabling for the candidate science program. These capabilities–long-lived power, communications, pre-deployment capabilities, mobility systems, and cyrogenic storage and curation–are described in this section.

7.1 Power and Communication

Long-lived deployed science experiments, which would address many of the highest-priority science Objectives identified here, require operations over time periods longer than the Artemis III surface mission. Power sources that enable surviving and operating through the lunar night are critical to accomplishing key science and exploration objectives, and lunar night operations are essential for a sustained presence on the Moon (LEAG 2019). In particular, science operations in polar regions, particularly in permanently shadowed regions and through the passage of the terminator, may rely on the power capabilities encompassed by operating through the lunar night.

Beginning with Apollo 12, astronauts deployed the Apollo Lunar Surface Experiments Packages (ALSEP), consisting of a series of geophysical and environmental monitoring instruments connected to a central base station. These were powered by Systems for Nuclear Auxiliary Power (SNAP)-27 Radioisotope Thermal Generators (RTG) that provided 70 Watts of continuous power and permitted night survival and operations (Figure 7.1.1). A similar power source would enable multiple Investigations outlined in this report.

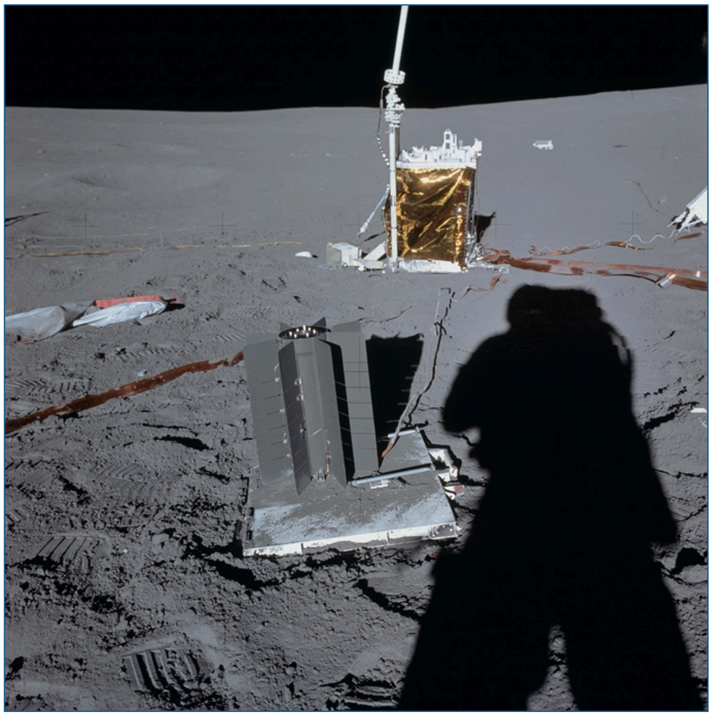


Figure 7.1.1. Apollo Image AS14-67-9366. Astronaut Alan Shepard's shadow over the Apollo 14 SNAP-27 RTG, as he photographed the deployed Apollo Lunar Surface Experiments Package. The central base station, which transmitted data from the instruments back to Earth, is visible in the background with its antenna deployed. Credit: NASA

A stationary solar array/mast in combination with batteries or fuel cells is also an option, as nighttime duration could be significantly lessened depending on the specific landing site of Artemis III near the south pole, especially if the site is located at one of the persistently illuminated regions (Speyerer et al. 2016). Fission nuclear power systems, such as NASA's Kilopower technology project, could also meet/exceed Artemis science power needs.

Communication capability is likewise needed to support deployed and *in situ* instruments, as well as any robotic precursor missions and the real-time audio/video communication recommended for field science in Section 6.

Finding 7.1-1: Several of the Investigations prioritized in this report would be maximally enabled by a long-lived power source and communications capability for deployed experiments.

> **Recommendation 7.1-1:** NASA should pursue solutions for long-lived power and communications to enable networked operation of ALSEP-like packages at multiple landing sites, as needed to enable meaningful progress on many of the Goals described in Section 5, and feeding forward to future Artemis missions.

7.2 Pre-deployment of Science Assets

At the time of writing of this report, the downmass capability of the HLS is not finalized. Existing mass allocations expected to be available on the HLS system for delivery of tools and payloads to the lunar surface are insufficient to achieve the full spectrum of science activities outlined by the external stakeholder community in our Guiding Documents. Our candidate program lays out a campaign of compelling and executable science investigations for the Artemis III mission based on the architecture as we currently understand it (Section 6), but the ability to pre-deploy science assets using a CLPS or other robotic lander would dramatically increase the capability of early Artemis landings.

Pre-deployment also offers operational benefits that would make the first HLS human landing safer with fewer unknowns. Such benefits could:

- Allow detailed survey and initial characterization of the human landing zone prior to human arrival
- Provide independent precision navigation aids for landing
- Provide video documentation of the historic human return, and monitor HLS-surface interactions while landing
- Enable contingency extension of surface stay time with extra consumables and spares
- Demonstrate surface rendezvous with applicability to sustained lunar operations and feed-forward to other destinations. Pre-deploy is a critical component of e.g. the Mars design reference architecture (DRA) 5.0 (Drake et al., 2009).

Finding 6.4-1, continued: Existing mass allocations expected to be available on the HLS system for delivery of tools and payloads to the lunar surface are insufficient to achieve the full spectrum of science objectives outlined by the stakeholder community.

> **Recommendation 7.2-1:** NASA should consider pre-positioning science assets in the vicinity of the Artemis III landing site. This could consist of an inert cache of tools/instruments to be accessed by crew upon arrival, and/or one or more instrumented landers or rovers for environmental monitoring.

7.3 Mobility

The Artemis III mission does not, as presently formulated, include availability of an unpressurized lunar rover for surface mobility of the crew. Pre-deployed assets could however also include mobility systems, which will be vital to the long-term exploration and development of the Moon. In addition to its size, the Moon's geography is complex and its resources dispersed. Evaluating potential sites for the future Artemis Base Camp reflects the immense scale of the lunar geography. Robust mobility systems will be needed to explore and develop the Moon and to explore Mars. A habitable mobility platform is a particularly important element for future missions, as the first mission to Mars will use a similar type of spacecraft.

Mobility on the lunar surface is a key factor for enhancing the scientific Investigations outlined in this report, as well as enabling for a range of complementary traverse measurements (e.g. gravimetry, magnetometry, ground penetrating radar). Mobility would also serve to increase the science capability of early Artemis landings by providing access to a diverse sample of geologic units and facilitating deployment of experiments over a broader area than can be accessed on foot during a single EVA. An unpressurized rover allows for a greater amount of field equipment to be carried on a traverse, giving the crew a wider assortment of tools to work with, and the flexibility to apply the right tool for the job at hand. Furthermore, an unpressurized rover would aid in being able to spend a greater amount of time out in the field, as the astronauts' energy exertion (i.e., life support consumable usage) will likely be less as they ride from location to location, instead of walking.

Finding 7.3-1: Crew mobility on the lunar surface is a key factor for enhancing the scientific investigations outlined in this report.

> **Recommendation 7.3-1:** NASA should include a rover or other mobility solution for crew use on the lunar surface starting as early in the Artemis program as possible, ideally for Artemis III.

7.4 Cryogenic Transport and Curation

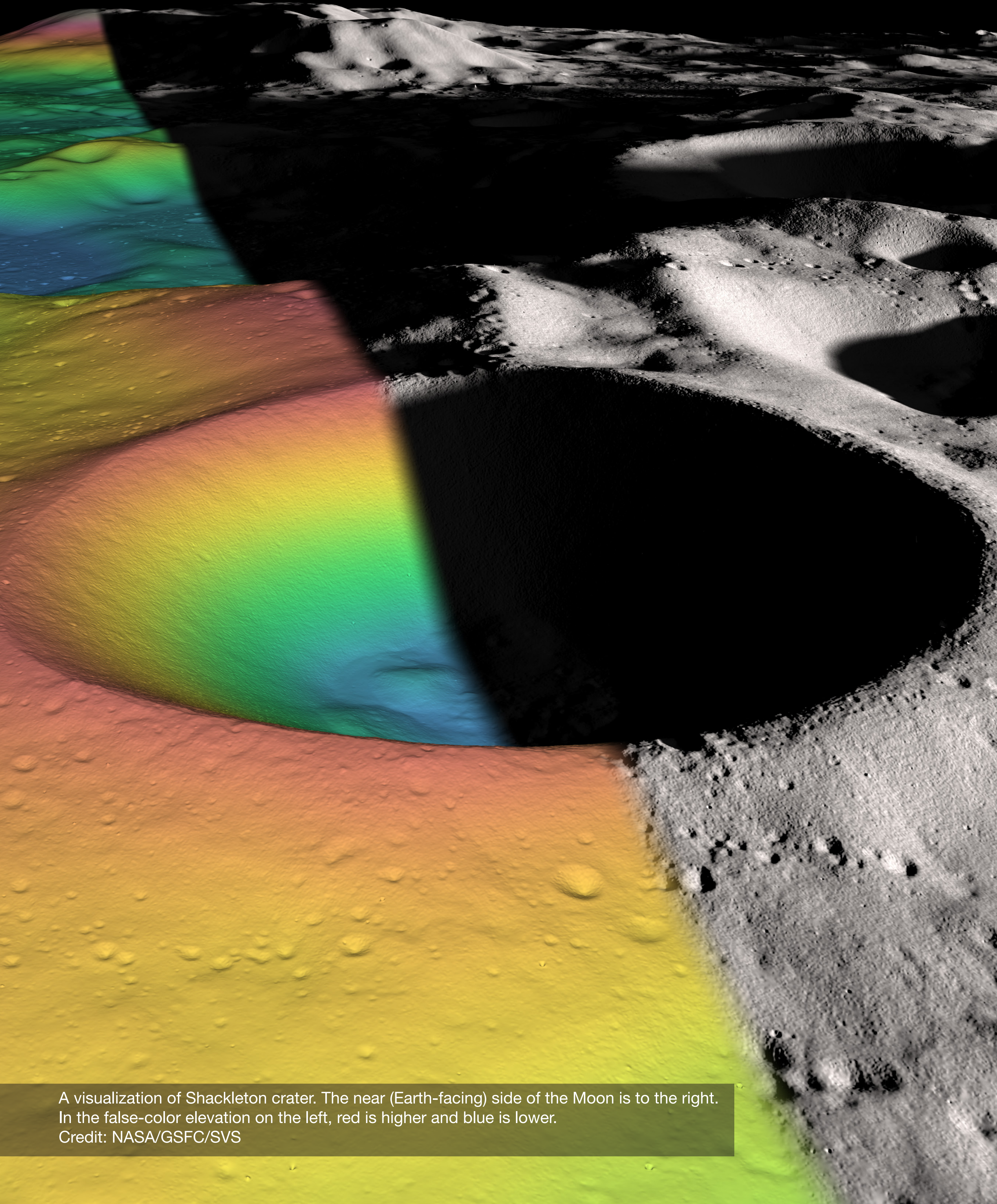
The ability to transport a sample from the surface of the Moon to curation facilities while continuously maintaining temperatures low enough that water ice and other relevant volatiles remain in the solid state with a low vapor pressure adds considerable value to sample return, especially for—but not limited to—the studies of volatile elements outlined in Science Objective 2. Cryogenic transport and curation will preserve aspects of the chemistry and stratigraphy of the samples that can be erased and/or compromised by reactions between liquid or gaseous H_2O and other volatile compounds. Reactions also occur at room temperature between water and minerals in lunar rock and regolith samples, and these reactions can obscure critical chemical, isotopic, and textural information. Apollo 16 sample 66095, known affectionately as the "rusty rock," is an example of a sample that would have benefitted from cryogenic vacuum transportation and curation. Cryogenic transport and curation also preserves textural information in core samples, at both macroscopic scales (e.g., the cryostratigraphy of a core sample) and microscopic scales (e.g., the textures present in volatile-rich deposits). Systems capable of maintaining samples under lunar cryogenic conditions will be of value not only to lunar sample return and curation but also sample return from Mars, comets, and potentially the ocean- and ice-world satellites of the outer planets.

Finding 7.4-1: The ability to conduct cryogenic sample return from the Moon to Earth increases the scientific yield of samples containing icy and/or volatile components.

> **Recommendation 7.4-1:** NASA should develop and implement the required hardware and operations to return a subset of the samples at temperatures low enough to preserve water ice and other low temperature volatiles of interest in the solid state throughout the entire journey from the lunar surface to Earth-based laboratories. Cryogenic sample return will increase the scientific fidelity of sample analyses of volatiles and ices. Minimizing the mass penalty for cryogenic sample return results in increased scientific yield of the mission since more mass can be allocated to the lunar samples instead of the sampling hardware.

SECTION 8

CARTOGRAPHIC CONSIDERATIONS



A visualization of Shackleton crater. The near (Earth-facing) side of the Moon is to the right. In the false-color elevation on the left, red is higher and blue is lower.

Credit: NASA/GSFC/SVS

8.0 Cartographic Considerations

Landing humans near the lunar South Pole and supporting surface operations for Artemis III will require the use of multiple lunar datasets from recent orbital missions. It is essential that each product use standardized and clearly defined geodetic information, consistent reference frames and coordinate systems, and cartographic products with known levels of accuracy and precision. Building on earlier work by the Lunar Mapping and Modeling Project (Noble et al., 2013) in developing standards and products (e.g., Rosiek et al., 2012) in preparation for Constellation, here we define the existing state-of-the-art for the lunar reference frame, existing cartographic products, and what will be needed to successfully implement the science defined in this document for the Artemis III mission.

8.1 Datasets

Recent lunar missions have collected a wealth of data of the lunar surface and the lunar environment. The Lunar Reconnaissance Orbiter (LRO) mission alone has delivered over 1.3 PB of data to NASA Planetary Data System, a volume of data far beyond that of any other planetary science mission. Along with LRO, data from the ISRO Chandrayaan-1 mission (specifically the Moon Mineralogy Mapper or M3 hyperspectral data, but also data from the Terrain Mapping Camera or TMC and other instruments), NASA GRAIL and LADEE missions, and Terrain Camera and Multiband Imager data from JAXA's SELENE mission provide a comprehensive modern view of the Moon. Data and derived products such as mosaics and topographic models from these missions serve as the basis for a number of studies and investigations, many of which provide context for future lunar exploration. These data are mission-enabling for Artemis III and are valuable assets in defining the science plan for Artemis III as well as placing results from the mission into a broader scientific context.

8.2 Reference Frame and Lunar Ephemeris

A critical aspect of any planetary dataset is the geodetic coordinate reference system (CRS) and ephemeris into which the data are placed. The CRS defines where on a planetary surface any pixel should be placed, and together with ephemeris defines the space and time of every observation as it is mapped onto a surface (often a 3D topographic model). The accuracy of the geodetic control has a direct impact on the accuracy of all tied spatial data products and provides a critical, single, reference frame that can significantly improve data usability for the non-spatial data expert. Consistent with the recommendations of the IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites (Seidelmann et al., 2007), the LRO mission uses the Mean Earth/Polar Axis (ME or MOON_ME) reference frame for all of its mapped data products, planetocentric coordinates, and the DE421 lunar orbit, orientation angles, and coordinate frame (LRO Project and LGCWG, 2008; Archinal et al., 2008; Folkner et al., 2008). While the opportunity to update the standard lunar reference frame is a possibility based on more recent data and modeling, such a change should occur early in the planning stages for Artemis III so that operations planning is done in the same updated system to optimize accuracy and precision and to minimize confusion or incorrect data being shared with the Artemis program.

Once mapped with well characterized accuracy and precision onto a standardized geodetic reference frame, controlled, foundational products (Archinal et al., 2018; Laura, 2020) form the basis for all reconnaissance and *in situ* mapping, mission planning, and surface operations. Currently three datasets comprise the most accurate global data onto which other products could be controlled: 1) the GRAIL GRGM1200A gravity model is a highly accurate and well understood planetary geoid for the Moon (Lemoine et al., 2014; Goossens et al., 2020); 2) At the poles, the Lunar Orbiter Laser Altimeter (LOLA) (Smith et al., 2010; Mazarico et al., 2011) elevation model (the LDEM GDR) provides a high-resolution topographic model (~118 m/pixel; Neumann et al., 2011); and 3) Between ±60° latitudes, the merged LOLA/SELENE Terrain Camera (TC) derived topographic model, SLDEM2015, is the highest resolution reference geodetic framework (Barker et al., 2016). The majority of large orbital datasets and derived products have not been tied to each other or controlled to a single geodetic lunar coordinate reference frame and thus remain largely independent products. These include the LRO Cameras [e.g., the Narrow and Wide Angle Cameras or NAC and WAC (Robinson et al., 2010)], M3 (Pieters et al., 2009; Boardman et al., 2011), SELENE TC (Haruyama et al., 2008) and MI (Ohtake et al., 2008) images, Apollo Metric (Edmundson et al., 2016; Nefian et al., 2012) and Panoramic Camera digitized photographs and mosaics, and derived digital mosaics (e.g., the WAC "morphology" mosaic, Wagner et al., 2015; and lunar photometric maps, Sato et al., 2014), and topographic models (e.g., the global, stereo-derived WAC topographic model or GLD100, Scholten et al., 2012 augmented with LOLA topography at the poles). Although some products are often internally consistent, the ability to compare products is limited because of this lack of geometric consistency.

At the lunar poles and at landing site scales, products such as NAC data, mosaics and stereo-derived elevation models (e.g., Henriksen et al., 2017) have the highest spatial resolution, but their level of control is highly variable depending on the source. Products are sometimes uncontrolled, absolutely controlled (i.e., controlled within themselves and registered to each other, and sometimes only loosely tied to other controlled products), or tied to a LOLA base. Color products (e.g., the WAC and MI global mosaic, M3 frames) needed for reconnaissance compositional mapping are also uncontrolled or only internally consistent. For data covering the polar regions, a standard polar-stereographic CRS provides a uniform base upon which all products can be most accurately mapped. The use of SPICE coordinates for a lander and/or rover (relative to the center of the planet) to describe the relative locations and positions of instruments, sample arms, cameras, etc. have long been used for Mars exploration, are well-developed and supported, and should continue to be useful for lunar surface exploration.

Finding 8.2-1: Accurate geodetic control of data has a direct impact on the accuracy of spatial data analysis and intercomparison of data products, vital both to mission planning and scientific analysis.

> **Recommendation 8.2-1:** Any needed updates to the standard lunar geodetic coordinate reference frame (e.g., currently used by LRO) should be identified in 2021, and foundational products should be mapped onto it and/or developed to use it directly. Establishing a standardized coordinate reference frames can significantly improve data reliability and reduce the risk of errors.

Finding 8.2-2: Standardization of cartographic and timing parameters is vital for interrelating the timing of crew activities and the timing of measurements from instruments.

> **Recommendation 8.2-2:** Standards for cartographic and time controls for surface measurements (photographs, video, and surface measurements) should be defined in the near term

so that those standards can be implemented in instrument development. This should also include high-fidelity time coding for all surface measurements time-synced with Earth in UTC.

8.3 Geologic Maps

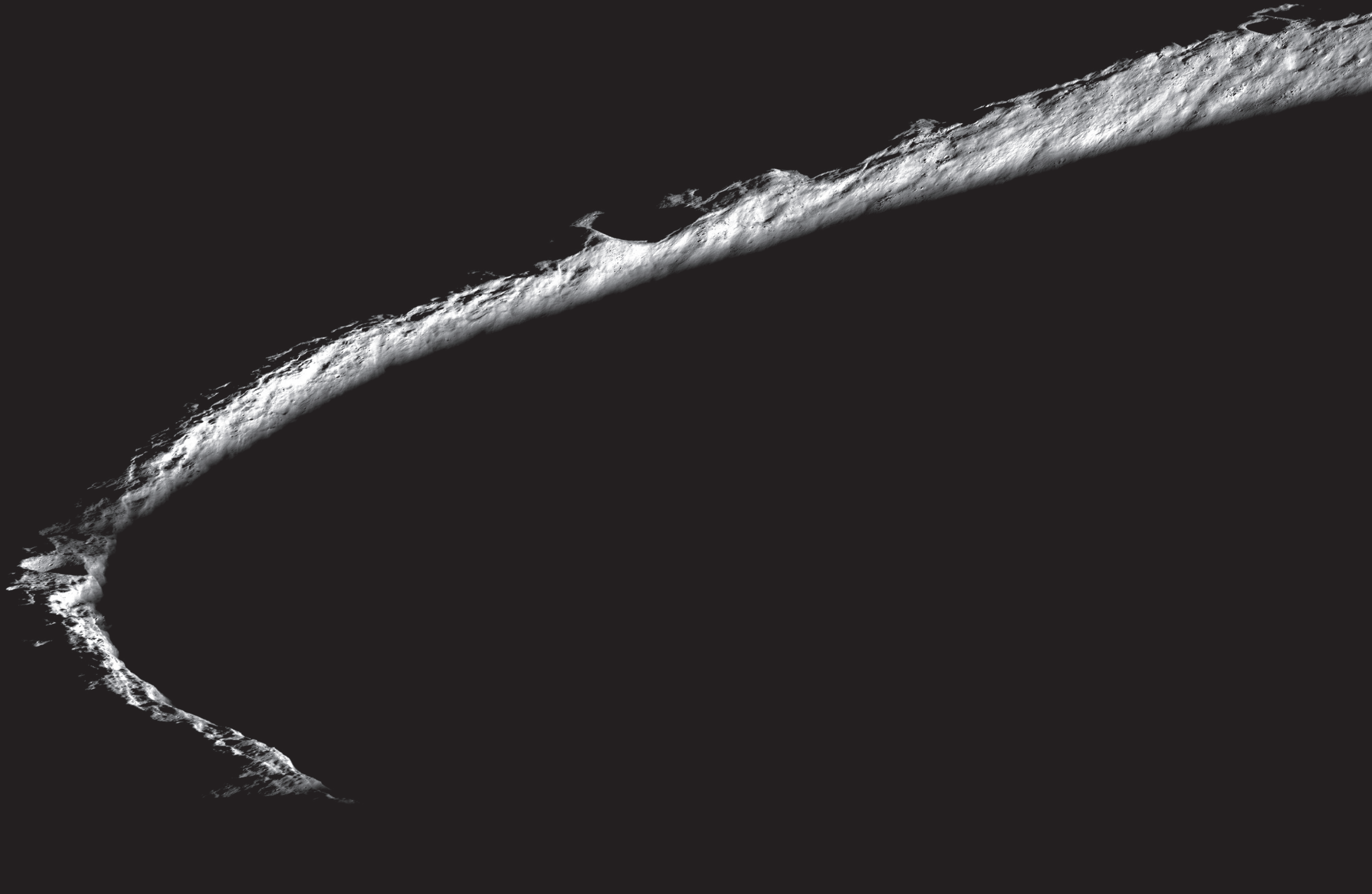
In preparation for the Apollo missions to the Moon, a coordinated effort to construct geologic maps at a range of scales was initiated by the United States Geological Survey (USGS). This effort resulted in geologic maps specifically focusing on individual candidate landing sites (e.g., Grolier, 1970; 1:25,000 scale) and at a regional scale for the nearside (e.g., Carr, 1966; 1:1,000,000). Over the past 10 years a handful of updated geologic maps have been started, including an updated global geologic map at 1:5M scale (Fortezzo et al., 2020) and a map of the South Pole at the 1:2,500,000 scale (Mest et al., 2016). These maps provide the geologic context of the region, yet new maps at reduced scales as was done in preparation for Apollo will facilitate planning and implementation of the Artemis III science.

Finding 8.3-1: During preparations for Artemis III, existing lunar data should be readily and easily available to scientists and mission planners. Accurate landing and localization during surface operations are dependent on the accurate and robust use of existing data.

> **Recommendation 8.3-1a:** We recommend maintaining sufficient funding to the PDS to maintain the online tools needed to search, access, and use lunar data.
>
> **Recommendation 8.3-1b:** To support the level of accuracy and precision needed for landing and surface operations, new cartographic products, including mosaics and topographic models, for the south pole should be developed using the highest quality data available (e.g., NAC and WAC frames, SELENE TC, MI, and Chandrayaan M3) and using the standard (possibly updated) lunar geodetic coordinate reference frame.
>
> **Recommendation 8.3-1c:** New derivation of higher-order data products from existing missions should also be supported where needed for Artemis III. For example, it is vital that more detailed geologic mapping of candidate landing sites be accomplished at a scale similar to what was done in preparation for Apollo.

SECTION 9

CONSIDERATIONS FOR LANDING SITE SELECTIONS



Spectacular oblique view of the rim of Shackleton crater (21 km diameter, 89.66°S, 129.20°E). While no location on the Moon stays continuously illuminated, three points on the rim remain collectively sunlit for more than 90% of the year. These points are surrounded by topographic depressions that never receive sunlight, creating cold traps that can capture hydrogen and other volatile species, NAC M1224655261LR.
Credit: NASA/GSFC/Arizona State University

9.0 Considerations for Landing Site Selections

The selection of a landing site for the Artemis III mission is outside of the scope of the activities of this SDT. The final Artemis III landing site will ultimately be selected on the basis of a variety of factors, some of which are presently unknown, including the capabilities of the HLS vehicles, the final launch window of the Artemis III mission, the availability of orbital data sufficient to inform site selection and landing site safety determinations, landing sites of surface exploration precursor missions, and architectural decisions relating to location of the Artemis Base Camp (Figure 9.1). Nevertheless, the scientific investigations enabled by the Artemis III mission will be very closely and synergistically linked to the complex geology of the Artemis III landing site and its associated surface and internal processes.

Accordingly, the SDT suggests the following factors be considered in the Artemis III site selection process in order to fully inform the ultimate selection of the Artemis III landing site, in addition to other physiographic parameters such as block abundance, crater frequency, and slope:

- Sufficient illumination for long-duration solar power stations, should such solutions be selected to enable long-lived surface experiments;
- Availability of a range of sizes of craters for radial traverses and sampling, which will inform our understanding of the impact process;
- Comprehensive sampling opportunities which will inform our understanding of the complex geology of the landing site and its link to both surface and internal processes;
- Accessibility of larger blocks to enable sampling of large crater ejecta;
- Proximity and accessibility of mostly or permanently shadowed regions to understand volatile processes;
- Proximity to multiple geologic units of differing time-stratigraphic age;
- Proximity to geologic units that enable specific, high-priority investigations (eg., basin chronology and PSRs)

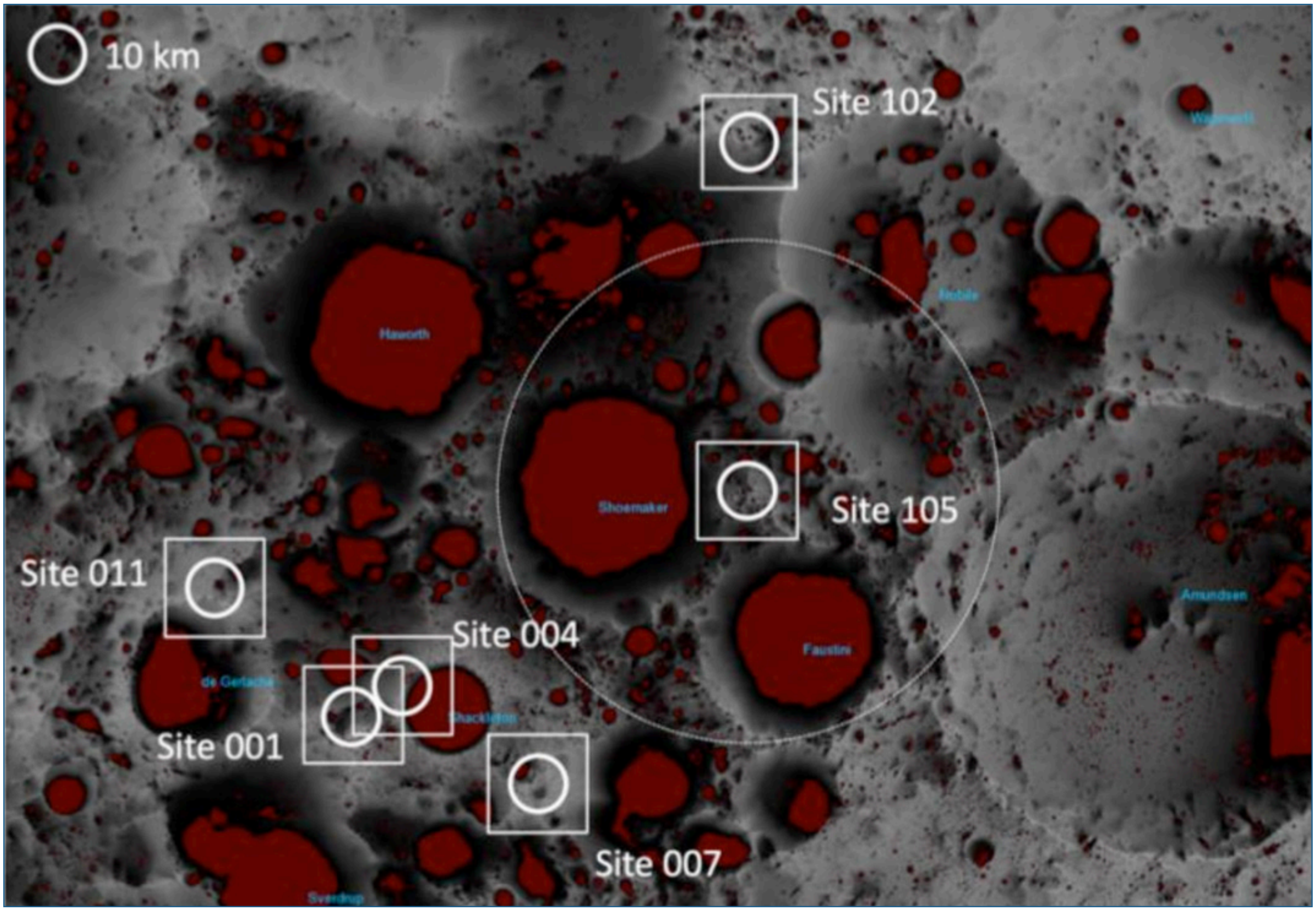


Figure 9.1. The landing site for the Artemis III mission has not been determined, but this image shows sites of interest near permanently shadowed regions, which may contain mission-enhancing volatiles. These sites may also offer long-duration access to sunlight, direct-to-Earth communication, surface slope and roughness that will be less challenging for landers and astronauts. Reproduced from NASA's Plan for Sustained Lunar Exploration and Development (2020).

SECTION 10

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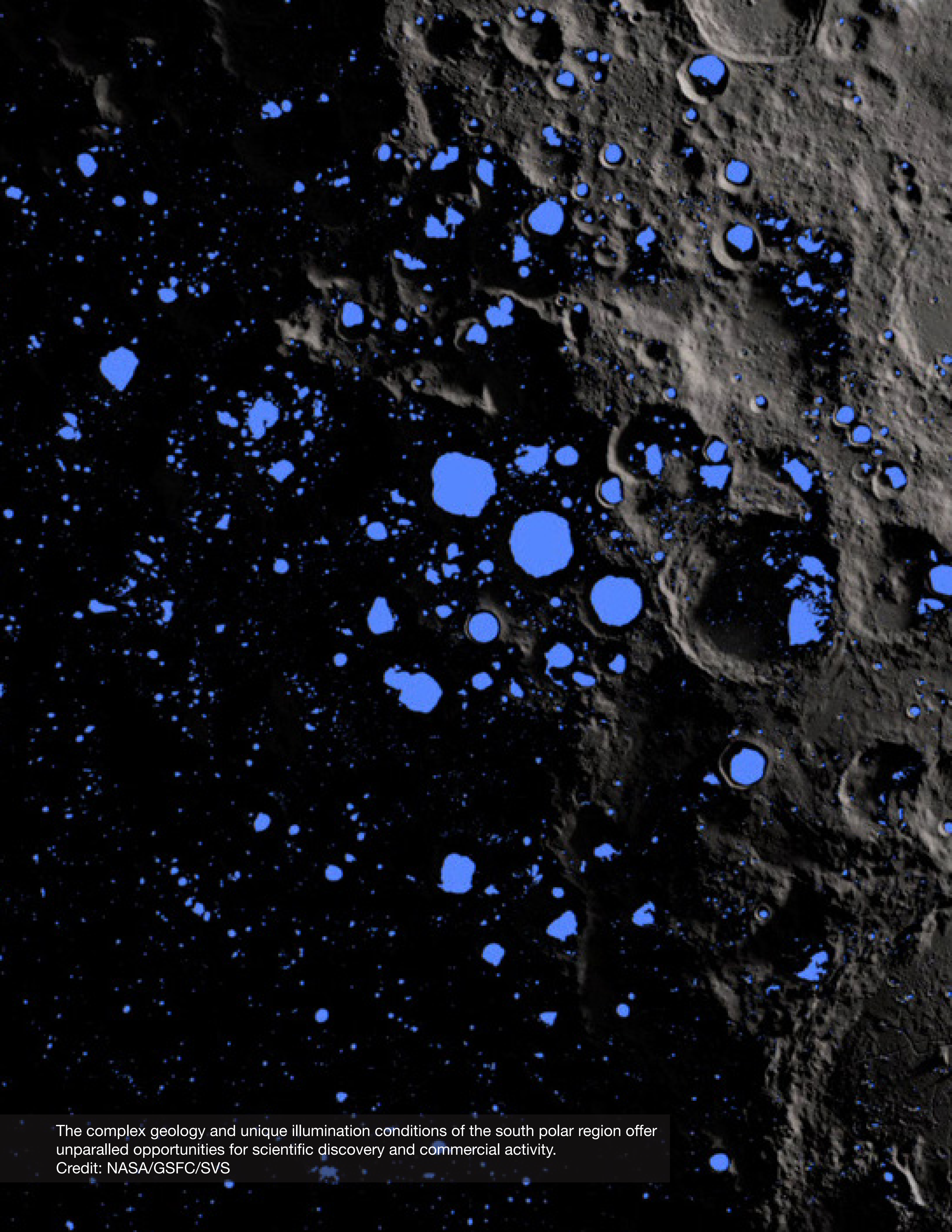

The complex geology and unique illumination conditions of the south polar region offer unparalled opportunities for scientific discovery and commercial activity.
Credit: NASA/GSFC/SVS

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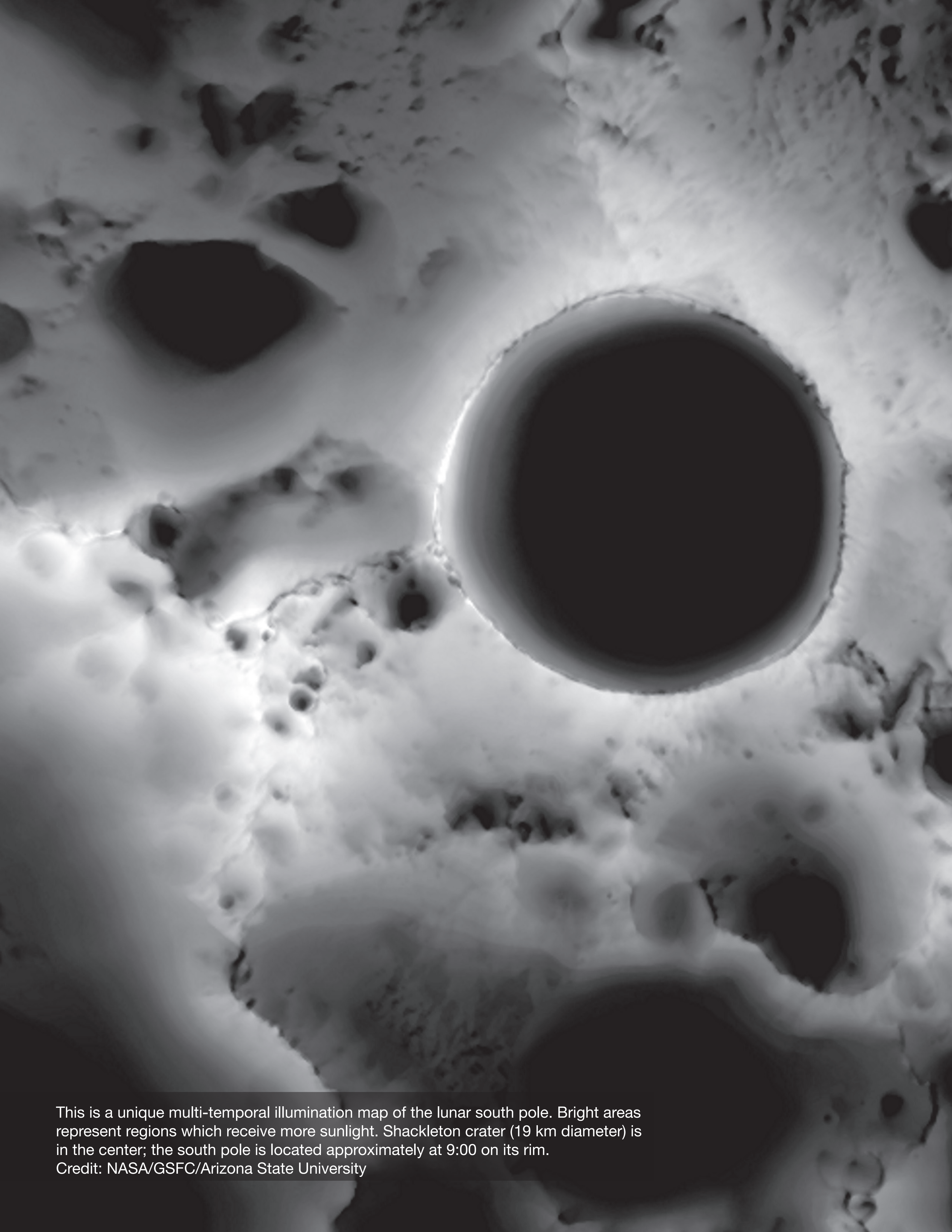
TABLE 1

SCIENCE TRACEABILITY MATRIX



This is a unique multi-temporal illumination map of the lunar south pole. Bright areas represent regions which receive more sunlight. Shackleton crater (19 km diameter) is in the center; the south pole is located approximately at 9:00 on its rim.
Credit: NASA/GSFC/Arizona State University

TABLE 1—SCIENCE TRACEABILITY MATRIX

Artemis Science Objective 1 Understanding Planetary Processes				
Science Goal	**Science Investigation**	**Traceability**	**Science Priority**	**Enabled by Artemis III**
1a. Formation of the Earth-Moon System	Understand the timing of the collision between the impactor and the proto Earth	ASM-NC1; ASM-NC2; ASM-3; LER Objective Sci-A-9	H	M
	1a-1. Establish the mechanisms, timing, and extent of volatile depletion in the Moon	ASM-NC2	H	Y
	Establish isotopic similarities and differences between the Earth and Moon to constrain the composition of the impactor	ASM-NC2	M	Y
	Constrain the physicochemical conditions and processes that operated in the protolunar disk	ASM-NC2	M	Y
	1a-2. Constrain the physicochemical conditions and processes that operated at the surface of the lunar magma ocean	ASM-NC2	H	Y
	Determine the composition and longevity of an early atmosphere on the Moon	ASM-NC2	L	M
	1a-3. Understand the size, chemical makeup, and timing of core formation	SCEM-2c; ASM-2c; LER Investigation Sci-A5E	H	Y
	Understand the relationship between volatiles in the interior of the Moon and those on the surface	ASM-4b	H	M
1b. Differentiation: Magma Oceans, Crust, and Mantle	**1b-1. Determine the extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation**	SCEM 3a; LER Investigation Sci-A-5A	H	Y
	Inventory the variety, age, distribution, and origin of lunar rock types	SCEM 3b; LER Investigation Sci-A-5	H	M
	Determine the composition, structure, and lateral variability of the crust on global scales.	SCEM 2a, 3c; LER Investigation-Sci-A-5C	H	M
	1b-2. Determine the bulk composition of the crust and mantle	LER Investigation-Sci-A-9A; LER Investigation-Sci-A-9B; LER Investigation-Sci-A-9C	H	Y
	Determine the vertical extent and structure of the megaregolith	SCEM 3e; LER Investigation Sci-A-7E	M	Y
	1b-3. Inventory, relationships, and ages of nonmare rocks.	LER Investigation-Sci-A-5A; SCEM 3d	H	Y

Artemis Science Objective 1
Understanding Planetary Processes

Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
1b. Differentiation: Magma Oceans, Crust, and Mantle (Continued)	Inventory, relationships, and ages of mare volcanics and related intrusive rocks	LER Investigation-Sci-A-5B	M	N
	Characterize the chemical/physical stratification and lateral heterogeneity in the mantle	LER Investigation-Sci-A-5D; SCEM 2b	H	M
	Determine the size, composition, and state (solid/liquid) of the core of the Moon	LER Investigation-Sci-A-5E; SCEM 2c	H	M
	Characterize the thermal state of the interior and elucidate the workings of the planetary heat engine (dynamo)	SCEM 2d	H	M
	Understand the history of the lunar magnetic field—and the process(es) that generated it—through paleointensity and paleopole determinations.	SCEM 2c, 2d; LER Investigation Sci-A-5E	M	Y
1c. Volcanism: Partial Melting, Eruptions, Flow Sequence and Compositions	Determine how magma is generated and transported to the surface.	LER Investigation-Sci-A-6A	M	N
	Determine how lava flows are emplaced on the Moon.	LER Investigation-Sci-A-6B	M	N
	Determine the physical characteristics of pyroclastic deposits and vents. Determine the compositional range and extent of lunar pyroclastic deposits	LER Investigation-Sci-A-5B	H	N
	Assessment of the volatiles driving lunar volcanic eruptions	LER Investigation-Sci-A-6D	H	N
	Determine the early thermal history of the Moon (Also captured in Differentiation & Tectonism)	LER Investigation-Sci-A-9C	H	M
	Determine the origin and variability of lunar basalts	SCEM 5a; LER Investigation-Sci-A-5B	M	N
	Determine the age of the youngest and oldest mare basalts	SCEM 5b; LER Investigation-Sci-A-5B	M	N
	Determine the flux of lunar volcanism and its evolution through space and time	SCEM 5d; LER Investigation-Sci-A-5B	M	N
	Determine the stratigraphy of the lunar maria	LER Investigation-Sci-A-8B	M	N

Table 1—4

TABLE 1—SCIENCE TRACEABILITY MATRIX

Artemis Science Objective 1
Understanding Planetary Processes

Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
1d. Tectonism: Deformation of the Crust and Thermal History	Determine the stratigraphy of the lunar highlands	LER Investigation-Sci-A-8C	M	Y
	Determine the tectonic history of the lunar crust	LER Investigation-Sci-A-8D	M	Y
	Determine the driving mechanism of shallow moonquakes	ASM-NC3	H	M
	Determine the physical parameters of a fault scarp	ASM-NC3	M	Y
	Determine age and context of samples of fault scarp related materials	ASM-NC3	M	Y
	Determine the early thermal history of the Moon (also captured in Differentiation & Volcanism)	LER Investigation-Sci-A-9C	H	M
1e. Impact Processes: Basins and Craters, Mixing of the Crust	Determine and understand the stages of formation of simple and complex craters, and multi-ring basins.	LER Investigation-Sci-A-7A; SCEM 6b	M	Y
	Determine how impacts modify, redistribute, and mix materials.	LER Investigation-Sci-A-7B; SCEM 6d	M	Y
	Determine the origin, extent, and differentiation/evolution of basin melt sheets.	LER Investigation-Sci-A-7C; SCEM 6a	M	Y
	Assess the possibility of impact-triggered magmatism.	LER Investigation-Sci-A-7D	M	Y
	Quantify the effects of planetary characteristics (composition, density, impact velocities) on crater formation and morphology	SCEM 6c	M	Y
1f. The Moon is a Natural Laboratory for Regolith Processes and Weathering on Anhydrous Bodies	Understand ballistic sedimentation/impact gardening	LER Investigation-Sci-A-4	M	Y
	Determine the production and evolution of the megaregolith.	LER Investigation-Sci-A-7E	M	M
	Search for and characterize ancient regolith	SCEM 7a; LER Investigation-Sci-A-4A; LER Investigation-Sci-B-2	M	M
	1f-1. Determine physical properties of regolith at diverse locations of expected human activity	SCEM 7b; LER Investigation-Sci-A-4E	H	Y

Artemis Science Objective 1
Understanding Planetary Processes

Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
1f. The Moon is a Natural Laboratory for Regolith Processes and Weathering on Anhydrous Bodies (Continued)	Understand regolith modification processes (including space weathering), particularly deposition of volatile materials	SCEM 7c; LER Investigation-Sci-A-4C	M	Y
	Search for extralunar material (including terrestrial debris) in the regolith	SCEM 7d; LER Investigation-Sci-B-2E	M	Y
	Assess the rate of mass wasting and lateral transport of regolith on the Moon in areas of significant topographic relief.	LER Investigation-Sci-A-4	M	M

Table 1—6

Artemis Science Objective 2 Understanding Character and Origin of Lunar Polar Volatiles				
Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
2a. Determine the Compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and with depth) of the volatile component in lunar polar regions.	**2a-1. Identification of surface frost composition**	SCEM 4a; VVM-SAT; ASM-4a, 4c; LER Investigation-Sci-A-3A; LER Investigation-Sci-A-3B	H	Y
	2a-2. Identification of surface frost locations in spatial context.	SCEM 4a; VVM-SAT; ASM-4a, 4c; LER Investigation-Sci-A-3A; LER Investigation-Sci-A-3B	H	Y
	2a-3. Temporal variability of frost	SCEM 4a, 8d; VVM-SAT ASM-4a, 4c; LER Investigation-Sci-A-3A; LER Investigation-Sci-A-3B	H	Y
	2a-4. Speciation of surface hydrogen	SCEM 4a; VVM-SAT; ASM-4a, 4c; LER Investigation-Sci-A-3A; LER Investigation-Sci-A-3B	H	Y
	2a-5. Understand surface hydrogen speciation spatial variability	SCEM 4a, 8d; VVM-SAT ASM-4a, 4c; LER Investigation-Sci-A-3A; LER Investigation-Sci-A-3B	H	Y
	2a-6. Spatial distribution of subsurface hydrogen	SCEM 4a; VVM-SAT; ASM-4a, 4c; LER Investigation-Sci-A-3A; LER Investigation-Sci-A-3B	H	Y
	2a-7. Determine distribution of micro cold traps across lunar surface within illuminated regions	SCEM 4a, 8d; VVM-SAT ASM-4a, 4c; LER Investigation-Sci-A-3A; LER Investigation-Sci-A-3B	H	Y
2b. Determine the source(s) for lunar polar volatile deposits	Measure the contribution of solar wind to surface hydroxylation	ASM-4e, 7c ; LER Investigation-Sci-A-4D	M	M
	Contemporary contribution of OH/H2O	SCEM 4b; ASM-NC1 ASM-NC2; ASM-3, 4e, 7c; LER Investigation-Sci-A-3D; LER Investigation-Sci-A-4D	M	Y
	2b-1. Origin of the polar volatiles	SCEM 4b; ASM-NC1; LER Investigation-Sci-A-3D; LER Investigation-Sci-A-4D	H	Y

Artemis Science Objective 2 Understanding Character and Origin of Lunar Polar Volatiles				
Science Goal	**Science Investigation**	**Traceability**	**Science Priority**	**Enabled by Artemis III**
2c. Understand the transport, retention, alteration, and loss processes that operate on volatile materials at permanently shaded lunar regions	**2c-1. Distribution of water/OH within a PSR**	SCEM 4c; ASM-NC1, ASM-3, 4b, 4c, 7c, 8d ; LER Investigation Sci-A-3; LER Investigation Sci-A-4E	H	Y
	2c-2. Subsurface temperatures	SCEM 4c; ASM-NC1, ASM-3, 4b, 4c, 7c, 8d; LER Investigation Sci-A-3; LER Investigation Sci-A-4E	H	Y
	2c-3. Determine the compositional/physical properties of H-bearing species of the regolith as a function of time	SCEM 4c; ASM-NC1, ASM-3, 4b, 4c, 7c, 8d; LER Investigation Sci-A-3; LER Investigation Sci-A-4E	H	Y
	Measure of the geotechnical properties (e.g,. density, porosity, particle size/distribution, compressive strength, cohesion/adhesion) of shadowed polar regolith	SCEM 4c; ASM-NC1, ASM-3, 4b, 4c, 7c, 8d; LER Investigation Sci-A-3; LER Investigation Sci-A-4E	M	Y
	Measure the electrostatic charging variability with tribocharging (natural and due to mechanical interactions), solar wind (electron and ion densities), and illumination conditions	SCEM 4c; ASM-NC1, ASM-3, 4b, 4c, 7c, 8d; LER Investigation Sci-A-3; LER Investigation Sci-A-4E	L	Y
2d. Understand regolith modification processes (including space weathering), particularly deposition of volatile materials in the near surface	Measure the contribution of hydroxyl (and other volatiles) in the regolith from UV + cosmic ray irradiation and meteoritic input	SCEM 4d; ASM-1, 4b, 4c, 7c, 8d; LER Investigation-Sci-A3; LER Investigation Sci-A-4E	M	Y
	Examine soils from special regions (e.g., paleoregoliths, shadowed, fresh craters, swirls, etc.)	SCEM 4d; ASM-1, 4b, 4c, 7c, 8d; LER Investigation-Sci-A3; LER Investigation Sci-A-4E	M	Y
	2d-1. Speciation of surface hydrogen	SCEM 4d; ASM-1, 4b, 4c, 7c, 8d; LER Investigation-Sci-A3; LER Investigation Sci-A-4E	H	Y

Table 1—8

TABLE 1—SCIENCE TRACEABILITY MATRIX

Artemis Science Objective 2 Understanding Character and Origin of Lunar Polar Volatiles				
Science Goal	**Science Investigation**	**Traceability**	**Science Priority**	**Enabled by Artemis III**
2e. Learn how water vapor and other volatiles are released from the lunar surface and migrate to the poles where they are obsorbed in polar cold traps	Identify the sources of the mid-latitude surface hydroxyl and water	SCEM 4b, 4c, 7c, 8d; ASM-1; LER Investigation-Sci-A-3D; LER Investigation Sci-A-4D	M-H	N
	Determine whether hydrogen products migrate poleward to the cold trap reservoirs	SCEM 4b, 4c, 7c, 8d; ASM-1; LER Investigation-Sci-A-3D; LER Investigation Sci-A-4D	M-H	N
	Systematically detect trace volatile species, like water, OH, and hydrocarbon in the exosphere	SCEM 4b, 4c, 7c, 8a, 8d; ASM-1; LER Investigation-Sci-A-3D; LER Investigation Sci-A-4D	M-H	N
	Detect volatile transport from mid- to high-latitudes as a function of driving space environmental (solar storm, meteor stream) condition	ASM-1, 4b, 4c, 7c, 8d; LER Investigation-Sci-A-3D; LER Investigation Sci-A-4D	M	N
2f. Understand the impact of human exploration on the lunar volatile record across the surface	**2f-1. Identify exploration-induced variations on volatile composition, form, and distribution on the lunar surface during sample collection and transport, during curation and analysis, and from landed activities**	SCEM 8a LER Investigation-Sci-A1 LER Investigation-Sci-A2 LER Investigation-Sci-A3	H	Y

Artemis Science Objective 3 Interpreting the Impact History of the Earth-Moon System				
Science Goal	**Science Investigation**	**Traceability**	**Science Priority**	**Enabled by Artemis III**
3a. Test the Cataclysm	Anchor the earliest recorded impact history of the Moon by determining the age of the oldest lunar basin, South Pole-Aitken	SCEM 1a; LER Investigation-Sci-A-8C	H	M
	Investigation 3a-1. Identify impact melt, impact ejecta, and exogenous (impactor) material in lunar samples to address the hypothesized Lunar Cataclysm	SCEM 1a; LER Investigation-Sci-B-1A; LER Investigation-Sci-B-1C	H	Y
3b. Understand changes to the Earth-Moon bombardment rate	**Investigation 3b-1. Refine the post-basin impact flux, including up to the present**	SCEM 1c, 1d; LER Investigation-Sci-B-1B	H	Y
	Determine the composition and source of impactors (also captured in 4c, Understand changing compositions of impactors with time, and the nature of the early Earth)	LER Investigation-Sci-B-1C	M	Y
	Characterize the impact hazard to the Earth-Moon system	SCEM 1d	M	M
	Determine the flux of impact ejecta and resulting formation rate of secondary impact craters on the Moon	SCEM 1e	M	M
3c. Understand the impact history of the landing site	**3c-1. Determine the sequence of individual craters and basins that influence local, regional, and global stratigraphy at the Artemis III landing site.**	LER Investigation Sci-A-8A	H	Y

Table 1—10

Artemis Science Objective 4
Revealing the Records of the Ancient Sun and Our Astronomical Environment

Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
4a. **Understand the history of the Sun, including the composition and flux of the solar wind**	Determine the chemical, petrographic, elemental and isotope stratigraphy of the regolith and search for horizons of paleoregolith.	SCEM 4e; LER Investigation-Sci-B-2A; LER Investigation-Sci-B-2B	M	Y
4b. **Understand the record of cosmic rays, gamma-ray bursts, and supernova**	Understand the record of isotopic variation in lunar regolith.	LER Investigation Sci-B-2	M	Y
4c. **Understand changing compositions of impactors with time, and the nature of the early Earth.**	Characterize meteoritic material, including terrestrial debris, found in the lunar regolith (also captured 3b-2, determine the composition and source of impactors)	LER Investigation Sci-B-1C; LER Investigation Sci-B-2E	M	Y
4d. **Understand the long-term variability in the solar constant**	Assess variability in the solar constant through detailed, long-term heat flow measurements	LER Investigation-Sci-B-2C	M	N

Artemis Science Objective 5
Observing the Universe and Local Space Environment from a Unique Location

Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
5a. Astrophysical and Basic Physics Investigations using the Moon	Viewing the Universe and the Seeds of Galaxy Structure in the "Dark Ages"	LER Investigation-Sci-C-1A	M	M
	Probing the Universe at the Highest Energies	LER Investigation-Sci-C-1B	L	N
	Key Tests of the Strong Equivalence Principle in Gravitational Field Theory	LER Investigation-Sci-C-1C	M	N
	Large Telescope at Earth-Sun L2	LER Investigation-Sci-C-1D	M	N
	Ultra high-resolution optical imaging of astronomical objects	LER Investigation-Sci-C-1E	M	N
	Detect gravitational waves	LER Investigation-Sci-C-1F	M	N
	Large Lunar Optical Telescope	LER Investigation-Sci-C-1G	M	N
	Search of exotic stable states of matter	LER Investigation-Sci-C-1H	L	N
	Assess variations in cosmic radiation through time	LER Investigation-Sci-B-2D	M	N
5b. Heliophysical Investigations using the Moon	**5b-1. Near-Lunar Electromagnetic and Plasma Environment**	LER Investigation-Sci-C-2A	H	Y
	The Moon's Remanent Crustal Magnetic Fields	LER Investigation-Sci-C-2B	M	N
	Magnetotail Dynamics at Lunar Orbit	LER Investigation-Sci-C-2C	M	N
	Imaging the Heliospheric Boundary	LER Investigation-Sci-C-2E	L	N
	Low-Frequency Solar and Exoplanet Radio Astronomy	LER Investigation-Sci-C-2F	M	N

Table 1—12

Artemis Science Objective 5
Observing the Universe and Local Space Environment from a Unique Location

Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
5b. Heliophysical Investigations using the Moon (Continued)	Imaging Geospace from the Moon.	LER Investigation-Sci-C-2G	L	N
	Analyze the composition of the Solar Wind	LER Investigation-Sci-C-2H	L	M
	High-Energy Optical Solar Observatory	LER Investigation-Sci-C-2I	L	N
	Sun's Role in Climate Change	LER Investigation-Sci-C-2J	L	N
	Understand and Predict Space Weather Impact on Robotic and Human Productivity	LER Investigation-Sci-C-2K	M	Y
	Characterize Radiation Bombardment on the Lunar Surface	LER Investigation-Sci-C-2L	M	Y
5c. Use the Moon as a platform for Earth-observing studies	Characterize the lightning distribution of the whole Earth disk	LER Investigation-Sci-C-3A	L	M
	Monitor the Variability of Earth's Atmosphere	LER Investigation-Sci-C-3B	M	N
	Detect Changes in the Earth's Albedo Variability	LER Investigation-Sci-C-3C	L	N
	Detect and Examine Infrared Emission of the Earth	LER Investigation-Sci-C-3E	M	N
	Develop Radar Interferometry of Earth from the Moon	LER Investigation-Sci-C-3F	M	N
	E/PO Opportunities Enabled by a Lunar-Based Earth Observatory (LBEO)	LER Investigation-Sci-C-3G	M	N
	Lunar-Based Earth Observatory Demonstration	LER Investigation-Sci-C-3H	M	M

Artemis Science Objective 6
Conducting Experimental Science in the Lunar Environment

Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
6a. **Investigate and characterize the fundamental interactions of combustion and buoyant convection in lunar gravity**	Investigate flame structure and instabilities near combustion limits, as defined by dilution, stoichiometry, temperature (low-temperature flames), etc.	LER Investigation-Sci-D-1A	M	N
	Use the sustained, low-gravity environment, in conjunction with measurements on Earth, to determine accurate values of diffusion coefficients required for all models of flame behavior	LER Investigation-Sci-D-1B	M	N
	Examine relatively large, lean weakly buoyant flames in hydrogen and methane in lunar gravity	LER Investigation-Sci-D-1C	M	N
	Construct and test multidimensional, dynamic models of flame phenomena and benchmark these against experiments in lunar gravity, as compared to earth gravity and any Space platform data	LER Investigation-Sci-D-1D	M	N
6b. **Perform tests to understand and possibly discover new regimes of combustion**	Investigate new regimes of combustion, such as flame balls, which have been proposed as the mechanism for sustaining flames at very lean limits in earth gravity	LER Investigation-Sci-D-2A	M	N
	Investigate rarefied gas combustion, either as premixed flames or diffusion flames	LER Investigation-Sci-D-2B	M	N
	How does a large premixed reactive mixture, or a large flame, behave when exiting to a vacuum or to very low atmospheric pressure?	LER Investigation-Sci-D-2C	M	N

Table 1—14

Artemis Science Objective 6 Conducting Experimental Science in the Lunar Environment				
Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
6c. Investigate interactions of multiphase combustion processes and convection in lunar gravity	Investigate the interaction of water mist with diffusion flames in lunar gravity	LER Investigation-Sci-D-3A	H	N
	Investigate the process of soot formation in lunar gravity	LER Investigation-Sci-D-3B	H	N
	Investigate the process of flame initiation and growth	LER Investigation-Sci-D-3C	H	N
6d. Use the unique environment of the lunar surface to perform experiments in the area of fundamental physics	Search for gravitational radiation using lunar-based, large-scale optical interferometry systems that take advantage of the seismic stability of the lunar surface	LER Investigation-Sci-D-4A	L	N
	Realize massive improvement in tests of general relativity (i.e. tests of equivalence principle) by placing active responder systems for lunar ranging	LER Investigation-Sci-D-4B	L	N
	Place state-of-the art atomic clocks and frequency standards in lunar laboratories for deep-space positioning, navigation and geodesy, avoiding limitations of terrestrial systems and atmospheric distortion and use these systems in fundamental tests of general relativity.	LER Investigation-Sci-D-4C	L	N
	Establish lunar-based mass spectrometry and related facilities for particle physics research (i.e. dark energy and dark matter studies, sterile neutrino searches, strangelet detection)	LER Investigation-Sci-D-4D	L	N
6e. Obtain experimental data to anchor multiphase flow models in lunar gravity	Test simple two-phase flow through straight channels at different inclinations under partial gravity	LER Investigation-Sci-D-5A	H	N
	Test two-phase flow through porous media/ packed beds under partial gravity	LER Investigation-Sci-D-5B	H	N
	Assess efficacy of boiling heat transfer under lunar gravity	LER Investigation-Sci-D-5C	H	N
6f. Study interfacial flow with and without temperature variation to anchor theoretical/ numerical models	Study low-Reynolds-number dynamic wetting in the presence of temperature gradients typical of the lunar environment and lunar gravity	LER Investigation-Sci-D-6A	H	M
	Study the behavior of liquid wicking under lunar gravity	LER Investigation-Sci-D-6C	M	N

Artemis Science Objective 6
Conducting Experimental Science in the Lunar Environment

Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
6g. Study behavior of granular media in the lunar environment	Obtain experimental data on gravity-driven, dense granular flows, such as flows out of a bin, corresponding to Earth-based design methods	LER Investigation-Sci-D-7A	H	M
	Investigate impact of accumulated lunar dust on exposed radiative, habitat, transportation, suit and optical surfaces, and understand how the electrical charge of the dust is important to this investigation (see science goal 7k)	LER Investigation-Sci-D-7B	H	N
	Study the chemical reactivity of Lunar dust on non-human biological model systems to to validate the Earth based assessment of lunar dust toxicity and the proposed Permissible Exposure Limit (PEL) to lunar dust	LER Investigation-Sci-D-7C	H	M
6h. Investigate precipitation behavior in supercritical water in lunar gravity	Measure salt deposition rate on heated surfaces in supercritcal water-salt solutions with and without flow	LER Investigation-Sci-D-8A	L	N
	Assess effects of Lewis number on homogeneous and heterogeneous salt precipitation in supercritical water-salt solutions	LER Investigation-Sci-D-8B	L	N
6i. Investigate the production of oxygen from lunar regolith in lunar gravity	Study separation behavior within melt of solids and bubbles during oxygen production using electrolysis	LER Investigation-Sci-D-9A	H	N
	Investigate multiphase heat-transfer schemes required for oxygen production employing regolith reduction	LER Investigation-Sci-D-9B	H	N
6j. Investigate the behavior of liquid-phase sintering in lunar gravity	Study the effect of solid volume fraction and varying operating conditions on liquid-phase sintering carried out on the lunar surface	LER Investigation-Sci-D-10A	M	N
6k. Study and assess effects on materials of long-duration exposure to the lunar environment	Analysis of human-emplaced materials from the Apollo era	LER Investigation-Sci-D-11A	H	N
	Early robotic placement of controlled material samples for evaluation in the lunar environment. Determining how well materials survive in the space environment directly impacts which materials might be best for additive manufacturing processes. Examine whether there are ways to use the harsh environment of space (e.g., ultraviolet (UV) radiation, atomic oxygen) to process materials or further advance the production of new materials and composites.	LER Investigation-Sci-D-11B	H	M

Table 1—16

Artemis Science Objective 6
Conducting Experimental Science in the Lunar Environment

Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
6l. Study the production of lunar concrete samples in the lunar environment	Study the mixing of materials delivered from Earth with lunar regolith, the use of molds, and lunar concrete perfomance and durability		H	M
	Study the lunar environment exposure of premade concrete samples with lunar simulant		M	M
6m. Study material flammability in the lunar environment	Study material flammability in partial gravity (lunar and Martian) where limited existing data and models suggests this to be a worst-case condition for fire safety		H	N
6n. Study the conversion of water-ice to gaseous hydrogen and oxygen, and liquefaction of gasses for propellant storage	Examine the influence of gravity on solid-liquid phase change of water ice including sedimentation of regolith in the liquid water. Also, study buoyancy driven flow of hydrogen and oxygen bubbles in partial-g during electrolysis. Investigte condensation of hydrogen and oxygen in partial -g during liquefaction process		H	N
6o. Study the water management in lunar plant growth systems	Study the stability of flow through a soil simulant and/or lunar regolith, and evaluate aeration and hydration of plant roots as a function of the capillary uptake vs gravity induced drainage		M	M
	Examine the stability of flow in hydroponic systems within capillary-dominated channels in that have compliant obstructions, and study the uptake and evaporation of water in a capillary based system		M	M
6p. Study pool and flow boiling in the lunar environment	Examine the influence of gravity on phase change, heat transfer, vapor bubble growth, coalescence and departure, and study partial gravity effects on vapor-liquid phase change, flow and heat transfer		L	N
6q. Study two phase adiabatic flow in the lunar environment	Examine the effect of gravity on interfacial shear, wave and slug formation, droplet entrainment and deposition processes, and study the effect of the gravity vector (magnitude and direction) on gas-liquid flows through various flow system components		M	N

Artemis Science Objective 6
Conducting Experimental Science in the Lunar Environment

Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
6r. **Perform tests of lunar resource recovery of O, Al, Fe or Mg using ionic liquids**	Understand the effects of partial-g on the complex fluid flow and mass transfer that needs to occur for ionic liquids to work, and investigate the performance of different, community-proposed ionic liquids and the materials derived from this process and their usefulness for various applications		L	N
6s. **Perform tests of biofilms on various materials and the effect of biocide surface coatings on biofilms**	Investigate the use of bacterial and fungal biofilm formation under lunar gravity on materials commonly used for surface habitats, and answer key questions about biofilm formation and mitigations, including effectiveness in spacecraft environment, safety concerns with any off-gassing, and equipment compatibility		M	M

TABLE 1—SCIENCE TRACEABILITY MATRIX

Artemis Science Objective 7
Investigating and Mitigating Exploration Risks

Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
7a. **Study the fundamental biological and physiological effects of the integrated lunar environment on human health and the fundamental biological processes and subsystems upon which health depend**	Conduct fundamental research to understand the physiological and biological effects of the lunar environment on non-human life forms	LER Investigation-Sci-D-14A	H	N
	Conduct fundamental research to understand the physiological, biological, and mental effects of the lunar environment on humans	LER Investigation-Sci-D-14B	H	N
7b. **Study the key physiological effects of the combined lunar environment on living systems and the effect of pharmacological and other countermeasures**	Evaluate the impact of the combined lunar environment with and without the use of countermeasures on cellular oxidative damage	LER-Objective Sci-D-15A	H	N
	Evaluate the impact of the combined lunar environment with and without the use of countermeasures on musculoskeletal system	LER-Objective Sci-D-15B	H	N
	Evaluate the efficacy of pharmacological countermeasures employed under variable radiation and gravity environments	LER-Objective Sci-D-15C	H	N
7c. **Evaluate consequences of long-duration exposure to lunar gravity on the human musculoskeletal system**	Determine if the lunar radiation environment alters the processes of reproduction, development, DNA damage and repair, metabolism, behavior, and aging	LER-Objective Sci-D-16A	H	N
	Evaluate the synergistic effects of the lunar radiation and the gravitational environment on the Moon and the microgravity environment during transit to and from the lunar surface	LER-Objective Sci-D-16B	H	N

Artemis Science Objective 7
Investigating and Mitigating Exploration Risks

Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
7c. Evaluate consequences of long-duration exposure to lunar gravity on the human musculo-skeletal system (continued)	Evaluate the use of radiation sensors and shielding materials using non-human biological systems	LER-Objective Sci-D-16C	H	N
	Evaluate multigenerational studies with simple multicellular and unicellular organisms to understand long term effects and adaptation to the lunar radiation environment	LER-Objective Sci-D-16D	H	N
	Understand the biological effects of lunar dust on model specimens/systems and interactions with the radiation environment	LER-Objective Sci-D-16E	H	N
7d. Study the effects of lunar radiation on biological model systems	Determine if the lunar radiation environment alters the processes of reproduction, development, DNA damage and repair, metabolism, behavior, and aging	LER-Objective Sci-D-17A	H	N
	Evaluate the synergistic effects of the lunar radiation and the gravitational environment on the Moon and the microgravity environment during transit to and from the Lunar surface	LER-Objective Sci-D-17B	H	N
	Use animal model systems to identify the physiological, cellular, biochemical, and molecular root causes for long duration effects of 1/6 g on the musculo-skeletal system as it relates to humans	LER-Objective Sci-D-17C	H	N
	Evaluate multigenerational studies with simple multicellular and unicellular organisms to understand long term effects and adaptation	LER-Objective Sci-D-17D	H	N
	Understand the biological effects of lunar dust on model specimens/systems and interactions with the radiation environment	LER-Objective Sci-D-17E	H	N

Table 1—20

Artemis Science Objective 7
Investigating and Mitigating Exploration Risks

Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
7e. **Use biological model specimens to conduct single and multigenerational studies on the long term effects of the lunar environment and transportation to and from the Moon on biological processes**	Investigate changes in the physiological microflora using animal model specimens	LER-Objective Sci-D-18A	H	N
	Investigate changes in immune system function using animal model specimens	LER-Objective Sci-D-18B	H	N
	Investigate the activation of latent viruses due to changes in immune functions and stress related to the lunar environment using cell culture model specimens and animal model specimens	LER-Objective Sci-D-18C	H	N
	Investigate changes in microbial virulence due to changes in gravity conditions. The study includes multicellular and unicelluar microbes and viruses	LER-Objective Sci-D-18D	H	N
	Investigate changes to normal biological functions at the physiological, cellular, biochemical, and molecular levels using a diverse array of biological model specimens	LER-Objective Sci-D-18E	H	N
7f. **Understand the effects/interactions of lunar gravity and the transitions between lunar gravity, microgravity, and Earth-normal gravity on reproduction and development, genetic stability, and aging**	Evaluate long-term effects and adaptation to the lunar gravitational environment of model specimens. Emphasis on in-situ analysis.	LER-Objective Sci-D-19A	H	N
	Evaluate if lunar gravity affects normal biological processes, e.g. metabolism, behavior, etc. in a variety of model organisms (cell culture, microbes, plants, small model animals)	LER-Objective Sci-D-19B	H	N
7g. **Study the influence of the lunar environment and its effects on short- and long-term plant growth, productivity (as a food source), palatability, and nutrition**	Evaluate the effects of lunar gravity on g-sensing, signal transduction, and growth response in a variety of model plants	LER-Objective Sci-D-20A	H	N

Artemis Science Objective 7 Investigating and Mitigating Exploration Risks				
Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
7h. Evaluate the use and effectiveness of model plants in ecological life support systems	Investigate the fidelity of replication of human microbial flora for variants, increase in virulence, and development of antibiotic resistance over thousands of generations (100 days = 5000 generations for some organisms)	LER-Objective Sci-D-21A	H	N
	Investigate the propagation of food sources/ crops for multiple generations and nutritional value. (could include primitive plant systems such as algae, not only higher plants)	LER-Objective Sci-D-21B	H	N
7i. Study the effect on microbes of long-duration exposure to the lunar environment	Study the effects of the lunar radiation environment and variable gravity on microbes	LER Investigation-Sci-D-12A	M-H	N
	Study the effect of regolith on microbial systems with respect to toxicity and nutrient availability	LER Investigation-Sci-D-12B	M-H	N
	Assess metabolic changes affecting bioprocessing potential, virulence, and sensitivity to antimicrobials.	LER Investigation-Sci-D-12C	M	M
7j. Assess the effect on plants of long-duration exposure to the lunar environment	Study the effects of the lunar radiation environment and variable gravity on plants	LER Investigation-Sci-D-13A	M-H	N
	Study the use of regolith as a growth medium for plants.	LER Investigation-Sci-D-13B	M-H	M
7k. Understand lunar dust behavior, particularly dust dynamics	Understand how dust transport shapes the physical and spectral properties of the lunar surface	LER Investigation Sci-A-1A; LER Investigation Sci-A-4A; LER Investigation C-2D	M	Y
	7k-1. Understand the properties of electrostatic lofting and levitation, and the role of electrical charging of the dust in the granular behavior of lunar regolih (see science goal 6g)	SCEM 8b; LER Investigation Sci-A-1A; LER Investigation Sci-A-3; LER Investigation Sci-C-2D	H	Y
	7k-2. Dust-Plasma Interaction on the Surface & Exosphere of the Moon	LER Investigation Sci-A-1A; LER Investigation Sci-A-3; LER Investigation Sci-C-2D	H	Y

Table 1—22

Artemis Science Objective 7
Investigating and Mitigating Exploration Risks

Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
7l. Understand lunar electrodynamics	**7l-1. Understand the plasma properties near the lunar surface and how they respond to external drivers, particularly across the terminator**	LER Investigation-Sci-C-2A	H	Y
	7l-2. Understand the origin of lunar surface potentials, how they evolve between sunlit and shadowed regions, and under what circumstances they pose a threat to exploration	SCEM 8b; LER Investigation-Sci-C-2A	H	Y
7m. Monitor real-time environmental variables affecting safe operations, which includes monitoring for meteors, micrometeors, and other space debris that could potentially impact the lunar surface	**7m-1. Establish a lunar environmental monitoring station to measure environmental variables such as temperature, vibration, dust collection, radiation, seismic activity, and gravity**	LER Investigation Sci-D-22A	H	Y
	7m-2. Provide real-time environmental information relevant to daily lunar operations	SCEM 8b; LER Investigation Sci-D-22B	H	Y

APPENDIX 1

TERMS OF REFERENCE

In NASA's Neutral Buoyancy Lab, teams are in the early stages of evaluating how astronauts would move around, set up habitats, collect samples and deploy experiments on the Moon in preparation for future missions on the lunar surface.
Credit: NASA

Appendix 1—Terms of Reference

1.0 Scope of Science Definition Team (SDT)

The SDT will define compelling and executable science objectives for the Artemis III mission, the first human mission to the surface of the Moon in the 21st century. The SDT will assess objectives for the mission to achieve the science goals articulated by NASA including investigation approaches, key surface science activities, and potential inputs into the concept of operations.

At the end of its work, the SDT will submit a final report to the Planetary Science Division that contains prioritized science objectives for all aspects of the Artemis III mission, including sampling strategies and science goals and priorities of deployable instrument packages.

1.1 Topics Within Scope of the SDT's Consideration

The SDT shall include the following elements in their discussions and final report:

1. Science goals, objectives, and investigations to be addressed by the Artemis III mission, based upon recommendations from the LEAG United States Lunar Exploration Roadmap, the 2007 NRC Scientific Context for the Exploration of the Moon report, the LEAG Advancing Science of the Moon report, and solicited public white papers, required in order to initiate execution of the Artemis Science Plan. These goals will also consider Decadal Survey recommended goals and objectives, but refined and focused in light of scientific advances since the Decadal Survey's publication and in order to ensure that Artemis science is compelling and executable.
2. Science traceability matrix, based upon the Artemis III reference mission architecture, to develop objectives and identify investigations that address those science goals.
3. Set of criteria to rank the relative priority of surface investigations and apply it to the investigations recommended.
4. Science requirements to address each investigation, including landing site characteristics, amount of crew interaction, measurement precision, spatial density, whether subsurface access is required, whether samples are required, longevity/duration for deployed experiments, etc.
5. Potential scientific synergy between Artemis III surface science and other planned or currently operating missions and deliveries (both NASA and non-NASA).

1.2. Topics Not Within Scope of SDT's Consideration

A number of elements will be excluded from the SDT's consideration. These topics will be redacted from any public input to the SDT and should not be discussed by the SDT. The SDT report shall not include advocacy, either for or against, or recommendations about any of the following topics. Due to the dynamic nature of the SDT process, NASA may modify this list as appropriate.

1. Particular instrument types, instrument builds, non-spacecraft capabilities (e.g., models, ground-based observatories). While some measurement requirements have generally been met by particular instruments, the SDT shall not recommend those particular instruments to the exclusion of other instruments (or combinations thereof) that could meet the requirement of measuring particular physical parameters.

2. The method, structure, content, or target of any mission formulation activity. This includes the direction, competition (e.g., AO, RFP), or invited contribution (i.e., from international partners) of mission components (e.g., spacecraft, instruments, inter-mission collaboration).
3. Any procurement activity in support of mission formulation activity. In instances where a need or opportunity outside of the committee's mandate is recognized, the SDT shall identify it for NASA to address separately.
4. Mission development costs or mission budget targets, either projected or recommended. All needed budgetary constraints will be provided by NASA.
5. Any specific Human Landing System or strategy.
6. Any potential NASA collaborations with specific US or non-US organizations.

Additionally, science goals, investigations, and requirements that are reviewed and determined by the SDT, as defined in 1.1., will be explicitly separated from mission requirements. Final mission plans will involve iterative meetings between SMD and HEOMD, taking the outcomes of this SDT into account.

2. Membership and Roles

The SDT consists of subject matter experts from the Civil Service and consultants from the scientific community occupying community leadership roles who have demonstrated significant and unique domain expertise and knowledge in lunar science and exploration. SDT members and consultants were selected by the Associate Administrator of the Science Mission Directorate, with the concurrence of the Director, Planetary Science Division.

Co-chairs

Renee Weber, NASA MSFC
Barbara Cohen, NASA GSFC
Samuel Lawrence, NASA JSC

Civil Servant Members

Jeremy Boyce, NASA JSC
Michael Collier, NASA GSFC
Caleb Fassett, NASA MSFC
Lisa Gaddis, USGS Astrogeology
John Gruener, NASA JSC
Jennifer Heldmann, NASA ARC
Noah Petro, NASA GSFC
Kelsey Young, NASA GSFC

Consultants

Amy Fagan, LEAG Chair
Carlé Pieters, SSERVI Chief Scientist
Juliane Gross, CAPTEM Lunar Sample Subcommittee Chair
Amanda Nahm, SMD PSD, will serve as the Executive Secretary for the SDT

The following civil servants will serve as ex officio members, in an observing capacity:
Sarah Noble, SMD Planetary Science Division
Debra Needham, SMD Exploration Science Strategy and Integration Office
James Spann, SMD Heliophysics division
Jake Bleacher, HEOMD
Julie Mitchell/Francis McCubbin, JSC curation
David Draper, NASA Office of the Chief Scientist

Organizational and Preparatory Pre-work

The SDT shall engage in organizational and preparatory pre-work ahead of the virtual in-person meetings as needed to successfully complete its work.

4. SDT Schedule

Meeting	Date	Participants
Science Goals/Objectives Meeting 1	Week of 07 Sep	Civil Servants Only
Science Goals/Objectives Meeting 2	Week of 14 Sep	All
Traceability/Surface Investigations Meeting 1	Week of 21 Sep	All
Traceability/Surface Investigations Meeting 2	Week of 28 Sep	Civil Servants Only
Traceability/Surface Investigations Meeting 3	Week of 05 Oct	All
Traceability/Surface Investigations Meeting 4	Week of 12 Oct	Civil Servants Only
Science Requirements Meeting 1	Week of 19 Oct	All
Science Requirements Meeting 2	Week of 26 Oct	Civil Servants Only
Science Requirements Meeting 3	Week of 02 Nov	All
Final Report to PSD	06 November	All

Consultants will attend Science Goals/Objectives Meeting 2 in order to provide community perspectives on the white papers submitted. They will attend Traceability/Surface Investigations Meetings 1 and 3 to provide input on their specific areas of expertise and will organize short reports from other community members to fill in holes in expertise not covered by the remaining committee membership. They will also attend Science Requirements Meetings 1 and 3 to ensure that the viewpoints from their respective communities are represented in the requirements definition and final report.

5. Input to and Comments for the SDT

The SDT will rely heavily on existing community-generated documents as the basis of their deliberations. Further, NASA invites input to the SDT process through the submission of short white papers, and has provided a public Artemis SDT webpage to receive those papers (https://www.lpi.usra.edu/announcements/artemis/). In addition, to provide opportunity for public comment two town halls will be held, the first in conjunction with the September LEAG meeting, the second once a draft report is released.

6. SDT Reports

The SDT will deliver a final report to the Planetary Science Division upon completion of team activities, anticipated by 30 Oct. 2020. PSD will make the report publicly available upon acceptance and work with HEOMD to integrate it into the Artemis Science Plan. The report is anticipated to contain a summary of submitted white papers, a science traceability matrix, a prioritized list of surface experiments, and requirements for each measurement, including (but not limited to: landing site characteristics, amount of crew interaction, measurement precision, spatial density, whether subsurface access is required, whether samples are required, longevity/duration for deployed experiments, etc).

Two weeks prior to submission of the report, a public comment period will open on the draft report. Public commentary will also be summarized in the report.

In addition to any other location, approved reports and public commentary will be made available on the Artemis SDT webpage.

Concurrence

Sarah Noble
Digitally signed by Sarah Noble
Date: 2020.08.31
16:53:46 -04'00'

Sarah Noble
Lead for Lunar Science,
Planetary Science Division

LORI GLAZE
Digitally signed by LORI GLAZE
Date: 2020.09.01
11:09:08 -04'00'

Lori S. Glaze, Ph.D.
Director, Planetary Science Division

DAVID BURNS
Digitally signed by DAVID BURNS
Date: 2020.09.02
11:27:59 -05'00'

David Burns
Acting Deputy Associate Administrator for Exploration,
Exploration Science Strategy and Integration Office

Approval

Thomas Zurbuchen
Digitally signed by Thomas Zurbuchen
Date: 2020.09.04
14:59:56 -04'00'

Thomas H. Zurbuchen, Ph.D.
Associate Administrator,
Science Mission Directorate

APPENDIX 2

SUMMARY OF COMMUNITY INVOLVEMENT

The Sun only grazes the horizon near the lunar poles. But because Malapert Mountain rises 7 kilometers (4.3 miles) above its surroundings, it enjoys prolonged periods of sunlight.
Credit: NASA/GSFC/ASU

12. Appendix 2: Summary of Community Involvement

Input from the planetary science community was solicited and captured at different stages during the Artemis III SDT process through several activities (see Appx.2-Table 1 for summary). Early input was solicited through white papers that focused on science objectives to be accomplished (rather than instrument or technology development recommendations) by the Artemis III mission; no limit was set to the number of white papers an individual or group could submit. These white papers provided valuable input in defining Artemis science goals and helped formulate the Science Traceability Matrix (STM). Community input was also solicited from community groups such as the Lunar Exploration Analysis Group (LEAG), Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM), CAPTEM Lunar Allocation Subcommittee (LASC), and Solar System Exploration Virtual Institute (SSERVI) during the process of refining the STM to ensure it captured priorities across the planetary community. Additional input was solicited from several individuals active in lunar science and exploration based on their specialized scientific background and topical knowledge, to ensure that key science areas were discussed, captured, and addressed in some degree in the STM and in this report.

An initial draft of this report was released to the public on October 16th, 2020 and the community was invited to submit feedback through an anonymous survey. A virtual Town Hall meeting, hosted by LEAG and SSERVI on October 22, 2020 ensured that the community had the opportunity to ask questions directed at the Artemis III Science Definition Team and voice additional input and any concerns. Questions were submitted online in advance of the Town Hall, as well as accepted live through a chat-box option during the virtual Town Hall event. Questions were presented by the moderator to the entire Science Definition Team who responded orally as well as through the chat box. Additional feedback was submitted before, during, and after the Town Hall about the draft report through an online system through October 26, 2020 and included the following guiding questions: (1) To what extent does the report define compelling and executable science objectives for the Artemis III mission? (2) What, if anything, is missing? (3) Do you agree with the Goals and Investigations prioritized for Artemis III? (4) Do you agree with Enabling Capabilities as presented in the report? (5) Do you agree with Landing Site Considerations as presented in the report? (5) Do you have any other feedback?

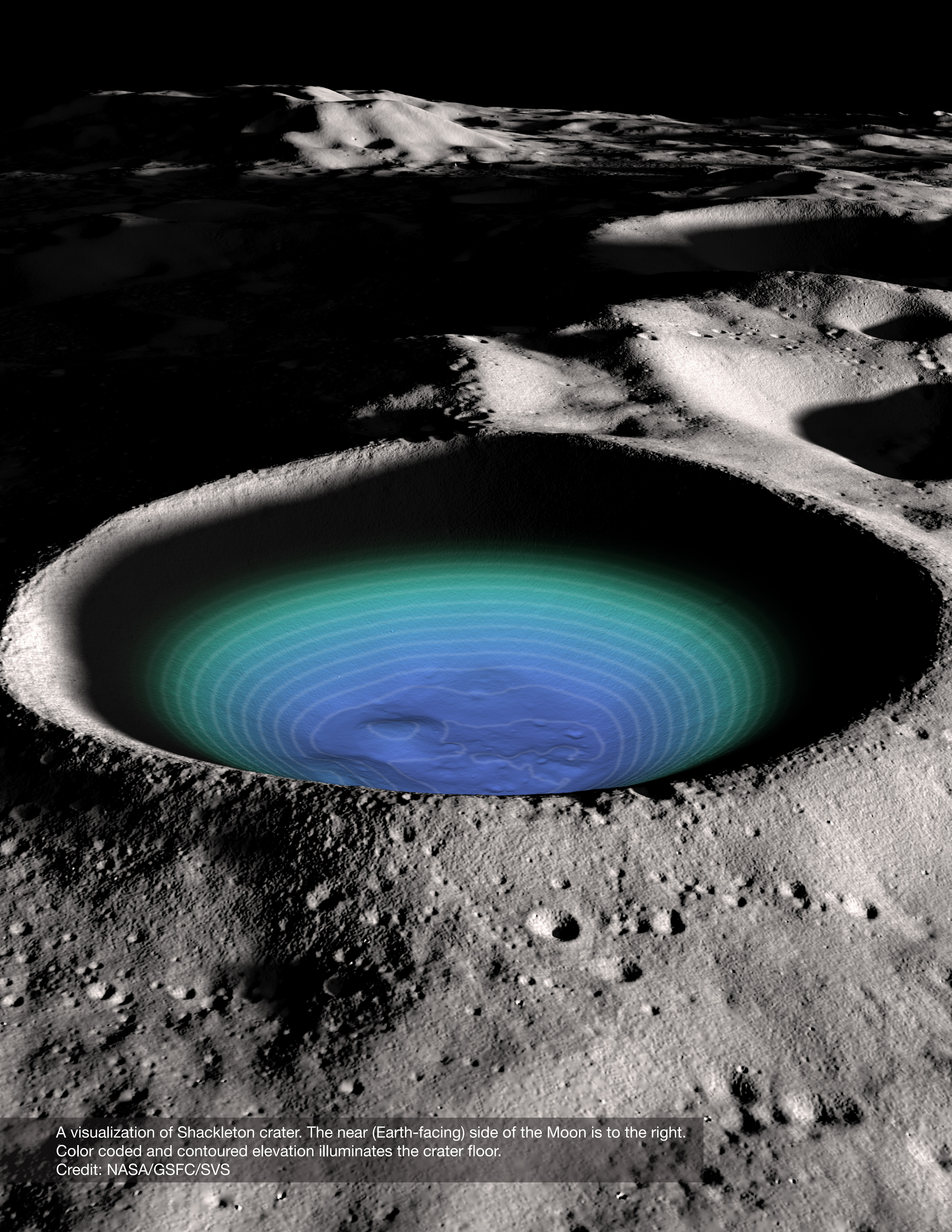
The anonymous community feedback and Q&A from the townhall were summarized, categorized, and captured in a report to the SDT. Submitted feedback touched on topics and issues specific to the Draft Report, and included concerns, suggestions for edits to the report, and additional input for the overall extended Artemis program. In addition to commenting on these topics, feedback emphasized the community's interest in Artemis III science, including assessing the special polar site geology and environment, collecting and returning a diverse and representative set of lunar samples, geophysical and geotechnical characterization of the polar environment, and using these investigations to prepare for sustained future Artemis missions and long-term human exploration goals. All of the feedback was appreciated, reviewed and discussed by the SDT to refine the Science Traceability Matrix (STM), adjust prioritization, strengthen the proposed program activities, and prepare the report.

Time	Input type	Usage
Early (prior to SDT and STM)	White papers	To guide the STM
During development of STM and SD draft report	Community groups input e.g. LEAG, CAPTEM, LASC, and SSERVI	To refine the STM and scope of the report
During SD draft report	Discussion with individual, active community members	To focus the report and ensure all science areas are discussed and captured appropriately
After SD draft report release	Survey, Comments on draft, Q&A during townhall meeting	To fine tune the STM and define the candidate science program

Table 1: Summary of input type, timing, and usage for community input/feedback.

APPENDIX 3

BIOGRAPHIES OF MEMBERS



A visualization of Shackleton crater. The near (Earth-facing) side of the Moon is to the right. Color coded and contoured elevation illuminates the crater floor.
Credit: NASA/GSFC/SVS

Appendix 3: Biographies of Members

Chairs

Renee Weber, Chair
NASA Marshall Space Flight Center

Weber received a bachelor's degree in physics with a focus on geophysics from the University of California, Berkeley in 2000, and a doctorate in earth sciences with a concentration in planetary geophysics from the University of California, San Diego in 2007. Following graduate school, she was awarded a Chateaubriand Postdoctoral Fellowship through the Embassy of France in the United States. She spent 2008 at l'Insitut de Physique du Globe de Paris, where she conducted independent research in planetary seismology in partnership with the French seismometer instrument team for the current Mars InSight mission. As a Shoemaker Postdoctoral Fellow at the U.S. Geological Survey's Astrogeology Science Center in 2009, she performed formative research that established the first direct seismic constraint on the size of the Moon's core.

Dr. Renee Weber currently serves in the Senior Technical position of Chief Scientist at NASA's Marshall Space Flight Center. In this role, Weber provides strategic leadership to a multidisciplined technical organization with responsibility for oversight of the formulation, maturation, design, development and operation of research, technology, and flight projects. Weber is a current Co-Investigator on the InSight geophysical mission to Mars and a member of the SEIS instrument science team. She was formerly a Guest Investigator on the GRAIL lunar gravity mission. Her scientific expertise includes extensive experience with processing and analyzing the Apollo lunar seismic data, as well as seismic data derived products such as velocity profiles and structure models.

Barbara Cohen, Chair
NASA Goddard Space Flight Center

Dr. Barbara Cohen is currently a planetary scientist at NASA Goddard Space Flight Center. She earned her BS in Geology from the State University of New York at Stony Brook and her PhD in Planetary Science from the University of Arizona. Her main scientific interests are in geochronology and geochemistry of planetary samples from the Moon, Mars, and asteroids. She is a Principal Investigator on multiple NASA research and space flight projects, including Lunar Flashlight, a lunar cubesat mission that will be launched in 2021 as an Artemis-1 secondary payload, and the PITMS, a mass spectrometer manifested aboard the Astrobotic Peregrine lander for a lunar surface mission in 2021. She has served in science and leadership roles for the Mars rovers Spirit, Opportunity, Curiosity, and Perseverance as well as the Lunar Reconnaissance Orbiter. Dr. Cohen provides subject-matter expertise on strategies to meet science and human exploration goals and objectives within NASA and has served on the executive committees for both the Lunar Exploration Analysis group and the Mars Exploration Program Analysis Group.

Samuel Lawrence, Chair
NASA Johnson Space Center

A planetary scientist at the Johnson Space Center (JSC), Dr. Samuel Lawrence serves as the JSC lead scientist for lunar exploration. A member of the Lunar Reconnaissance Orbiter (LRO) Camera Science Team, Dr. Lawrence has been heavily involved in LRO spacecraft development, testing, operations, and science since 2007.

Dr. Lawrence is an influential leader of the planetary science community. He has served in leadership roles in the Lunar Exploration Analysis Group (LEAG) since 2013 and served as the LEAG Chair from 2018-2020. Lawrence has chaired or participated in numerous LEAG special action teams since 2005. Dr. Lawrence is also a voting member of CAPTEM, has served on the Planetary Science Subcommittee of the NASA Advisory Council, was the Chair of the NASA Cartography and Planetary Geologic Mapping Working Group from 2012-2016, and was the chair of the NASA-USGS Mapping and Planetary Spatial Infrastructure Team from 2014-2016.

Dr. Lawrence was awarded the 2017 NASA SSERVI Susan Mahan Niebur award for outstanding early career contributions to Exploration science.

Members

Jeremy Boyce, Member
NASA Johnson Space Center

Boyce received a bachelor's degree in geology in 1997 and a master's degree in geochemistry in 2000, both from the University of California, Los Angeles, followed by a doctorate in geochemistry from the Massachusetts Institute of Technology in 2006. Boyce was awarded a National Science Foundation postdoctoral fellowship at Arizona State University to develop a method to use mineral apatite as a barometer of volatile species in terrestrial magmas. He completed additional postdoctoral training at the California Institute of Technology, with research focused on lunar apatite and the lunar volatile record.

Dr. Boyce currently serves as a planetary scientist in the Astromaterials Research and Exploration Division (ARES) at NASA's Johnson Space Center. His research interests center on geochemical method development and applications aimed at understanding the formation of planets and moons, especially with respect to volatile elements.

Michael Collier, Member
NASA Goddard Space Flight Center

Collier is currently a civil servant scientist at NASA GSFC and the Associate Lab Chief of the Geospace Laboratory in the Heliophysics Science Division. He has fabricated, calibrated, commanded, and analyzed data from many flight hardware projects over more than 33 years in the field. He is a Co-investigator on many missions, including Solar Orbiter and Solar wind Magnetosphere Ionosphere Link Explorer (SMILE). He has launched eight instruments into space as hardware Principal Investigator: five low energy neutral atom imagers, two soft X-ray imagers, and an electron spectrometer. He has broad research interests covering solar wind, heliospheric, terrestrial magnetospheric, and outer planets physics. Particular research topics include soft X-ray emission from solar wind charge exchange, solar wind particles and fields, the study of low-energy neutral atoms, lunar and outer planets particles, fields, and exosphere studies including lunar and airless body surface potentials and Jovian magnetometer data analysis.

Caleb Fassett, Member
NASA Marshall Space Flight Center

Fassett received a bachelor's degree in astrophysics and geosciences from Williams College in 2002, and a doctorate degree in geological sciences from Brown University in 2008. From 2008-2011, he stayed at Brown as a postdoctoral research associate, focused on analysis of early mission data from the MESSENGER mission to Mercury. In 2016, he joined the planetary science group at Marshall Space Flight Center (MSFC) after 5 years at Mount Holyoke College in Massachusetts. Dr. Fassett's scientific research focuses on using a combination of remote sensing, geologic mapping, and numerical modeling to better understand planetary surfaces and geomorphological processes. In graduate school, he discovered and first documented the deltas and paleolake in Jezero crater, which is the landing site for the Mars 2020 rover. He has also worked extensively on how observations of impact crater populations on planetary surfaces can be used to infer their geologic history. In addition to this scientific research, Dr. Fassett supports several engineering activities at MSFC, including the Human Landing System natural environments working group.

Lisa Gaddis, Member
U.S. Geological Survey and the Lunar and Planetary Institute

Gaddis was educated at the University of Hawaii at Manoa (Ph.D.), Brown University (M.S.), and Vassar College (A.B.). Gaddis is the current Director of the Lunar and Planetary Institute in Houston, Texas. Prior to joining LPI, Gaddis was a Research Geologist with the Astrogeology Science Center of the U.S. Geological Survey in Flagstaff, Arizona. She worked with USGS between 1990 and 2020 as a planetary scientist, cartographer, and data archivist. Her research interests include analyzing the composition, physical properties, and geologic history of planetary surfaces in the Solar System using remote sensing data at a variety of wavelengths.

John Gruener, Member
NASA Johnson Space Center

Gruener received a B.S. in Aerospace Engineering from the University of Texas at Austin (1986) and an M.S. in Physical Sciences from the University of Houston - Clear Lake (1994). John E. Gruener works in the Astromaterials Research and Exploration Science (ARES) Division at the NASA Johnson Space Center (JSC) in Houston, Texas. Arriving at JSC in 1986, Gruener's initial assignments included working as an aerospace/system engineer on space shuttle mission design, the space station assembly sequence, and as a member of NASA's Exploration Program Office for the Space Exploration Initiative. Since 1994, his efforts have focused more on the scientific nature of space exploration, working as a research scientist in soil chemistry and mineralogy laboratories for plant growth facilities in bioregenerative life support systems, in support of the Mars Exploration Rover (MER) missions, and as a project scientist in the NASA Constellation Program's Lunar Surface Systems Project Office. He has participated in several Lunar Exploration Analysis Group (LEAG) specific action teams (SATs), including Lunar Polar Volatiles SATs 1 and 2, Next Steps on the Moon SAT, and the Resource Prospector SAT. John currently works in the Exploration Science Office in ARES, providing mission planning for NASA's human/robotic exploration of the Moon and cis-lunar space, ARES's in-house robotic mission development efforts; and leading ARES's development of planetary surface simulants. He is also the Project Manager for the NASA's Lunar Surface Innovation Initiative (LSII) Lunar Simulant Project.

Jennifer Heldmann, Member
NASA Ames Research Center

Heldmann received a bachelor's degree in astrogeophysics from Colgate University in 1998, a master's degree in space studies with a minor in geology from the University of North Dakota in 1999, and a doctorate in planetary science from the University of Colorado at Boulder in 2003. Following graduate school, she was awarded a National Research Council (NRC) postdoctoral position at NASA Ames Research Center. She is currently a Research Scientist at NASA Ames, where she focuses on studies of the Moon and Mars. This research includes improving our understanding of lunar volatile deposits and studies of recent water on Mars through analysis of spacecraft data, numerical modeling, and terrestrial analog fieldwork.

Dr. Heldmann served as Principal Investigator (PI) of NASA's FINESSE (Field Investigations to Enable Solar System Science & Exploration) Team from 2013-2019 and led field expeditions focused on science, technology, and mission operations for enabling future lunar surface exploration with robots and humans. She is the Principal Investigator for NASA's RESOURCE (Resource Exploration and Science of Our Cosmic Environment) team focused on science, technology, and mission operations to enable *in situ* resource utilization (ISRU) of lunar polar volatiles to enable sustained human exploration of the Moon. She previously served on the Science Team, Payload Team, and as the Observation Campaign Coordinator for NASA's Lunar Crater Observation and Sensing Satellite (LCROSS) mission to study the permanently shadowed regions of the lunar poles. She is a member of the VIPER (Volatiles Investigating Polar Exploration Rover) mission Science Team, helping to develop real-time science operations protocols and science analysis tools for this rover mission to explore lunar polar volatile deposits. She is the recipient of numerous awards, including the NASA Exceptional Scientific Achievement Medal, NASA SSERVI (Solar System Exploration Research Virtual Institute) Coradini Award for Exploration, Antarctic Service Medal, multiple NASA Group Achievement Awards including the FINESSE, RESOURCE, and Mojave Volatile Prospector projects as PI, and a NASA Superior Achievement Award for Science.

Noah Petro, Member
NASA Goddard Space Flight Center

Petro received a bachelor's degree in geology with a focus on lunar remote sensing from Bates College in 2001, and a doctorate in Geology with a concentration in planetary geology from Brown University in 2007. Following graduate school, he was awarded a NASA Postdoctoral Position at the NASA Goddard Space Flight Center in Greenbelt, Maryland. As a co-investigator on the Moon Mineralogy Mapper, he was responsible for generating a targeting plan during operations, and led analysis of the distribution of volatiles at volcanic features.

Dr. Noah Petro currently serves as the lab chief of the Planetary Geology, Geophysics, and Geochemistry lab in the Solar System Exploration Division at NASA's Goddard Space Flight Center. Petro is the Project Scientist for the Lunar Reconnaissance Orbiter mission in orbit at the Moon. He was formerly a Co-Investigator on the Chdandryaan-1 lunar orbiting mission. His scientific expertise includes experience with processing and analyzing the remote sensing data, as well as the interpretation of spectral data and their derived products.

Kelsey Young, Member
NASA Goddard Space Flight Center

Dr. Kelsey Young received a bachelor's degree in Environmental Geosciences from the University of Notre Dame in 2009, and a master's degree and a doctorate in Geological Sciences from Arizona State University in 2012 and 2014, respectively. She then completed a postdoc at NASA Goddard Space Flight Center, followed by a two-year exploration scientist position at University of Texas, El Paso/Jacobs at NASA Johnson Space Center. Young is now a Research Space Scientist at NASA Goddard Space Flight Center, while also working under a Memorandum of Understanding with NASA Johnson Space Center. Young is a field geologist, studying volcanic and impact cratering processes on Earth as a comparison to the Moon, Mars, and other planetary bodies. She has led numerous NASA-funded projects and field campaigns and is currently serving as the Co-Lead for NASA GSFC's Goddard Instrument Field Team, where she focuses on the integration of field portable instrumentation into field geology and crewed planetary surface exploration.

Young's current work focuses on the integration of science and human spaceflight, with a current focus on the Artemis Program. In this role, she provides science input to the operations and tools teams who are defining the path forward to lunar surface exploration. She serves on the Exploration Extravehicular Activity Operations team in NASA JSC's Flight Operations Directorate to help define how science and operations will integrate in both the lead up to and real-time operations during Artemis missions. She also serves on the NASA Leadership Team for NASA Astronaut Geoscience Training and is the current Human Exploration Chair on the Lunar Exploration Analysis Group.

Community Representatives

Amy Fagan, Community Representative
Western Carolina University

Dr. Amy L. Fagan earned a Bachelor of Science degree in Geology with honors from Washington and Lee University in 2006. She graduated from the University of Notre Dame in 2013 with a PhD in lunar petrology under the direction of Dr. Clive Neal, studying impact and volcanic processes on Mars and the Moon. She then completed a post-doctoral fellowship at the Lunar and Planetary Institute (LPI) under the direction of Dr. David Kring, where she investigated the bombardment history of the Moon through petrographic analysis of Apollo collection samples. She joined the faculty of the Geosciences and Natural Resources Department at Western Carolina University in 2014 as an Assistant Professor and was promoted to Associate Professor on 1 July 2020. Her current research examines the thermal evolution of the Moon through lunar basalts and troctolites and the bombardment history of the Moon through lithic clasts in lunar regolith breccias. Her research has expanded to include lunar and HED meteorites as well as ultramafic rocks in North Carolina. She currently serves as the Chair of the Lunar Exploration Analysis Group (LEAG). In 2020, Dr. Fagan was awarded the Susan Mahan Niebur early career award from NASA's Solar System Exploration Research Virtual Institute (SSERVI) for making "significant contributions to the science or exploration communities."

Juliane Gross, Community Representative
Rutgers University and NASA Johnson Space Center

Gross received a master's degree in petrology in 2005 with a focus on metamorphic petrology of terrestrial continent-continent collision zone samples and a doctorate in 2009 in experimental petrology with a concentration on subduction zone fluid-rock interactions from the Ruhr-University Bochum, Germany. Following graduate school, she was a Postdoctoral Fellow at the Lunar and Planetary (LPI) in Houston from 2009 to 2011, during which she began her research in planetary sample science with a focus on lunar meteorites and Apollo samples. Her research placed small scale observations of lunar and martian samples into planetary scale processes, ranging from testing the lunar magma ocean hypothesis to calculating the water content of parental melts in the martian mantle. From 2011-2015 she was a Research Scientist at the American Museum of Natural History (AMNH) in New York City. In 2013 she was awarded the NASA Early Career Fellow in Planetary Sciences for her work on lunar meteorites.

In 2015, Gross became an assistant professor for planetary sciences at Rutgers, the State University of New Jersey and the director of the Earth and Planetary Science E-beam facility at Rutgers. Two years later, she earned tenure and was promoted to associate professor. Her current research at Rutgers University focuses on investigating the formation and evolution of differentiated planetary bodies, e.g., the Moon and Mars, as well as understanding early Solar System processes by examining primitive bodies such as asteroids. In 2017, she was named a Chancellor's Scholar at Rutgers University and is currently building the Rutgers Planetary Science Track for undergraduates in the Department for Earth and Planetary Sciences. Since 2019, Gross is the Deputy Curator for Apollo samples at NASA Johnson Space Center in Houston. In this role she helps to protect, preserve, and distribute samples from the Moon for present and future scientific studies of Solar System exploration and history. Outside of Rutgers and NASA, she serves as the chair of the lunar allocation subcommittee of the Curation and Analyses Planning Team for Extraterrestrial Materials (CAPTEM).

Carle Pieters, Community Representative
Brown University

Dr. Pieters' research focuses on remote compositional analyses and surface processes. She has extensive laboratory experience with lunar samples and meteorites and implemented the multi-user Reflectance Experiment Laboratory (RELAB) for the community. She has been a productive lunar and asteroid scientist and participated as a science team member on exploration missions to the Moon and asteroids. Dr. Pieters was PI of the Moon Mineralogy Mapper (M3) on the Indian Chandrayaan-1 mission and a Co-I on NASA's Dawn Mission to Vesta and Ceres.

Dr. Pieters is an elected fellow of the AAS, Meteoritical Society, GSA, AAAS, and AGU and the recipient of the AAS/DPS Kuiper Prize, NASA Exceptional Scientific Achievement Medal, COSPAR International Cooperation Medal, and SSERVI Shoemaker Medal.

Ex Officio Members

Jake Bleacher, Ex Officio Member
NASA Headquarters

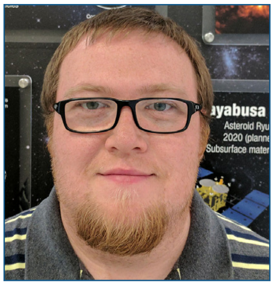
Bleacher earned a BS in Geosciences from Franklin and Marshall College and a Ph.D. in Geological Sciences from the Arizona State University. During his Ph.D. research, he worked on the European Space Agency's Mars Express Mission by conducting geologic mapping of the initial images acquired of the large Tharsis province volcanoes by the Mission's High Resolution Stereo Camera (HRSC). Dr. Bleacher joined NASA's Goddard Space Flight Center (GSFC) as a NASA Postdoctoral Program Fellow after which he was hired by NASA as a research scientist. Dr. Bleacher's research focuses on understanding the volcanic history of the Earth, Moon, and Mars by remote sensing mapping and field work. Upon joining the NASA workforce, he began supporting the Constellation Program Office to conduct studies examining potential landing sites and developing science traverse plans to help define requirements for hardware on the lunar surface.

Dr. Bleacher is a planetary geologist who is currently serving as NASA's Chief Exploration Scientist for the Human Exploration and Operations Mission Directorate (HEOMD) at NASA headquarters. In this role, he is a science advocate for NASA technology and architecture development that is intended to enable human exploration of the Moon, deep space and beyond. He also serves as a primary contact with NASA's Science Mission Directorate (SMD) and the science community external to NASA. He applies a strong interest in both scientific research and human exploration to his current role at NASA headquarters.

Dave Draper, Ex Officio Member
NASA Headquarters

Deputy Chief Scientist David Draper joined NASA's Office of the Chief Scientist in July 2019 from NASA Johnson Space Center in Houston, Texas. He served as the Manager of the Astromaterials Research Office, Astromaterials Research and Exploration Science Division, Exploration Integration and Science Directorate, from June of 2009 to June of 2019. Draper has 28 years of professional experience in studying the Earth, Moon, planets, and Solar System. These scientific studies explored frontier questions regarding characteristics, processes, and events of and on Earth, the Moon, and Mars. His scientific specialty is in experimental simulations at high temperatures and pressures of processes occurring within planetary interiors, such as the solidification of planetary magma oceans like those thought to have occurred on the Moon and Mars. He also has fifteen years' experience organizing the annual Lunar and Planetary Science Conference, serving as Program Committee Chair and co-Chair from 2009-2019.

Draper's education and training were in the geochemical and experimental study of terrestrial basalts, using them as probes of Earth's upper mantle and to understand processes occurring in subduction zones and mantle plumes. This background was directly extensible to the study of rocky bodies in the Solar System. He hails from California and the Pacific Northwest, and has held academic positions in Texas and New Mexico, as well as postdoctoral appointments in the United Kingdom and Australia.



Francis McCubbin, Ex Officio Member
NASA Johnson Space Center

McCubbin is the astromaterials curator at NASA's Johnson Space Center within the Astromaterials Research and Exploration Science Division. As head curator, he is responsible for protecting the scientific integrity of NASA's priceless astromaterials collections and distributing select samples to the global scientific community for further examination. His research focuses on understanding the abundance, distribution, and origin of water and other volatiles in the inner solar system, including Earth, Moon, Mars, and asteroids. Furthermore, he is interested in deciphering the thermal and magmatic evolution of the terrestrial planets, moons, and asteroids. This work is accomplished through a combination of experimental petrology and micro-beam sample analysis techniques of astromaterials.

Julie Mitchell, Ex Officio Member
NASA Johnson Space Center

Mitchell received Bachelor's degrees in aerospace engineering and geological sciences from The University of Texas at Austin in 2008. From 2008 - 2013, she worked as an engineer in the Crew and Thermal Systems Division at the NASA Johnson Space Center (JSC), where she certified crew and environmental monitoring hardware for the Space Shuttle and International Space Station (ISS). In 2013, Mitchell transferred to the Astromaterials Acquisition and Curation Office at JSC while beginning graduate school. She completed her doctorate in geological and planetary science from Arizona State University in 2017, after which she returned to the JSC Curation Office full-time.

Dr. Mitchell currently serves as the Artemis Curation Lead and Curator of Ices and Organics. In these roles, she is preparing NASA for sample return from cold, volatile-rich Solar System bodies such as comets, the Moon, and outer planet icy moons. She develops volatile-bearing comet and lunar simulants, which allow sample preservation techniques, hardware, and procedures to be evaluated. Mitchell is currently building cold curation operations plans for the agency for initial cold sample recovery, processing, and curatorial characterization, handling, dissemination to the science community, and long-term sample storage. Her focus as Artemis Curation Lead is on lunar polar sample return for Artemis, including sample collection, sample preservation, contamination control, crew safety, and lunar surface operations. She is currently the Principal Investigator for a lunar simulant technology development project and a Co-Investigator on several lunar volatiles studies. Dr. Mitchell's scientific expertise is in reflectance and emission spectroscopy of planetary analog materials, planetary remote sensing, and field geology.

Amanda Nahm, Executive Secretary
NASA Headquarters

Dr. Nahm earned her BA in geology with a minor in astronomy from the University of Colorado at Boulder in 2006 and her Ph.D. in geology from the University of Nevada, Reno in 2010. Her research interests focus primarily on tectonics on bodies in the Solar System with solid surfaces, such as the Moon, Mars, Europa, and Enceladus. Dr. Nahm has been a high school science teacher, an Alexander von Humboldt Postdoctoral Research Fellow at the German Aerospace Center (DLR) in Berlin, and has held postdoctoral research positions at the University of Idaho, the University of Texas at El Paso, and the Lunar and Planetary Institute in Houston.

Nahm joined NASA as a program officer in the Science Mission Directorate's (SMD) Planetary Science Division (PSD), employed by ASRC (Arctic Slope Regional Corporation) Federal, in August 2020. She is the deputy lead program officer for the FINESST program for graduate students (Future Investigators in NASA Earth and Space Science and Technology) and has served as a caucus member for several other research and analysis programs. In addition to these responsibilities, she also is the lead for the Gateway Lunar Discipline Working Group, tasked with identifying objectives for utilization of the Gateway for lunar science. She is also the lead author on the chapter about lunar tectonics for the upcoming New Views of the Moon 2 volume.

Debra Needham, Ex Officio Member
NASA Headquarters

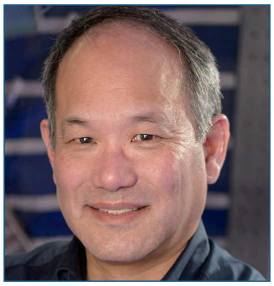
Originally from Houston, Texas, Dr. Needham (née Hurwitz) earned her BA in Geology from Pomona College in 2007, her MS in Geosciences from Brown University in 2009, and her PhD in Geosciences from Brown University in 2012, with her dissertation investigating the formation and distribution of lava channels on planetary surfaces in the inner Solar System. After earning her Ph.D., Dr. Needham completed two postdoctoral fellowships: first, in 2012 at the Lunar and Planetary Institute in Houston, where she investigated the composition and distribution of the South Pole-Aitken impact melt sea, and second, in 2015 at Goddard Space Flight Center in Greenbelt, Maryland, where she continued her investigation of lava flow emplacement processes on the Moon and Mars through field work investigations in analog sites in Hawaii, Iceland, and New Mexico.

Dr. Needham joined NASA in 2016 as a research scientist in the Heliophysics and Planetary Science Group (ST-13) at Marshall Space Flight Center (MSFC), where she continued her research of volcanic eruptions, in particular identifying volcanic eruptions as a potential source for polar volatiles identified on the Moon. While at MSFC, Dr. Needham also worked with several teams of engineers to integrate science objectives and instrumentation into future habitat and lunar lander design concepts. Dr. Needham is currently a program scientist in the NASA Science Mission Directorate's Exploration Science Strategy and Integration Office (ESSIO), where she works to set strategy for integrating science into human exploration endeavors on the Moon and Mars. Dr. Needham coordinates across divisions within SMD, with other NASA directorates, and with international partners to ensure upcoming crewed missions are equipped to address high priority science objectives that have been championed by the science community.

Sarah Noble, Ex Officio Member
NASA Headquarters

Dr. Noble earned her Bachelor of Science in Geology, with honors, from the University of Minnesota in 1998, and her master's and doctorate in Geological Sciences from Brown University in 2000 and 2004, respectively. She spent time as a researcher at NASA JSC, NASA MSFC, and NASA GSFC, as well as a brief stint working for Congress as an AAAS Science and Technology Policy Fellow with the House Committee on Science and Technology. Her scientific research is focused on understanding space weathering processes on the Moon and other airless bodies using both spectroscopy and electron microscopy techniques.

At NASA Headquarters, Dr. Noble is the Lead for Lunar Science within the Planetary Science Division of the Science Mission Directorate. She is also the Program Scientist for the Psyche, VIPER (Volatiles Investigating Polar Exploration Rover), and LRO (Lunar Reconnaissance Orbiter) missions, and oversees several research and analysis programs, including SSERVI (Solar System Exploration Research Virtual Institute).



Kevin Sato, Ex Officio Member
NASA Ames Research Center

Dr. Sato earned his B.S. degree in Microbiology from UCLA and his Ph.D. in Biology from U.C., Irvine. He was an American Cancer Society and California Breast Cancer Research Program post-doctoral Fellow at The Scripps Research Institute in La Jolla, CA. He also worked at two start-up biotechnology companies in Silicon Valley.

Sato is the Program Scientist for Exploration in NASA's Biological and Physical Sciences Division (BPS), working on advancing fundamental research to the Moon and beyond across BPS Space Biology and Physical Sciences Programs. He has served NASA's Space Biology Program and its research community for over 20 years at NASA Ames Research Center, first as a contractor with Lockheed Martin and FILMSS (KBRwyle) and currently as a Civil Servant. As an Experiment Support Scientist, Payload Scientist, Project Scientist, and Deputy Project Manager, he supported and led numerous NASA Space Biology projects and flight missions in support of NASA-sponsored Principal Investigator science investigations on the space shuttle and ISS. He has served as the science lead for the development of several spaceflight hardware for the space shuttle and ISS. In addition, he was the risk manager for the Stratospheric Observatory for Infrared Astronomy (SOPHIA) Project at NASA ARC for observation instruments. As the Senior Project Scientist for Space Biology at NASA ARC and the acting BPS Space Biology Program Scientist, Kevin worked with the science community, across NASA Programs, field Centers, other government Agencies, and international space Agencies to advance fundamental space biosciences in support of exploration and pioneering science discoveries. During his detail to BPS, Kevin served as the BPS lunar science lead. He was the President of the American Society for Gravitational and Space Research (2019) and has served on the Society's Governing Board. He is an Associate Editor for npj Microgravity. He was a recipient of the NASA Silver Snoopy Award.

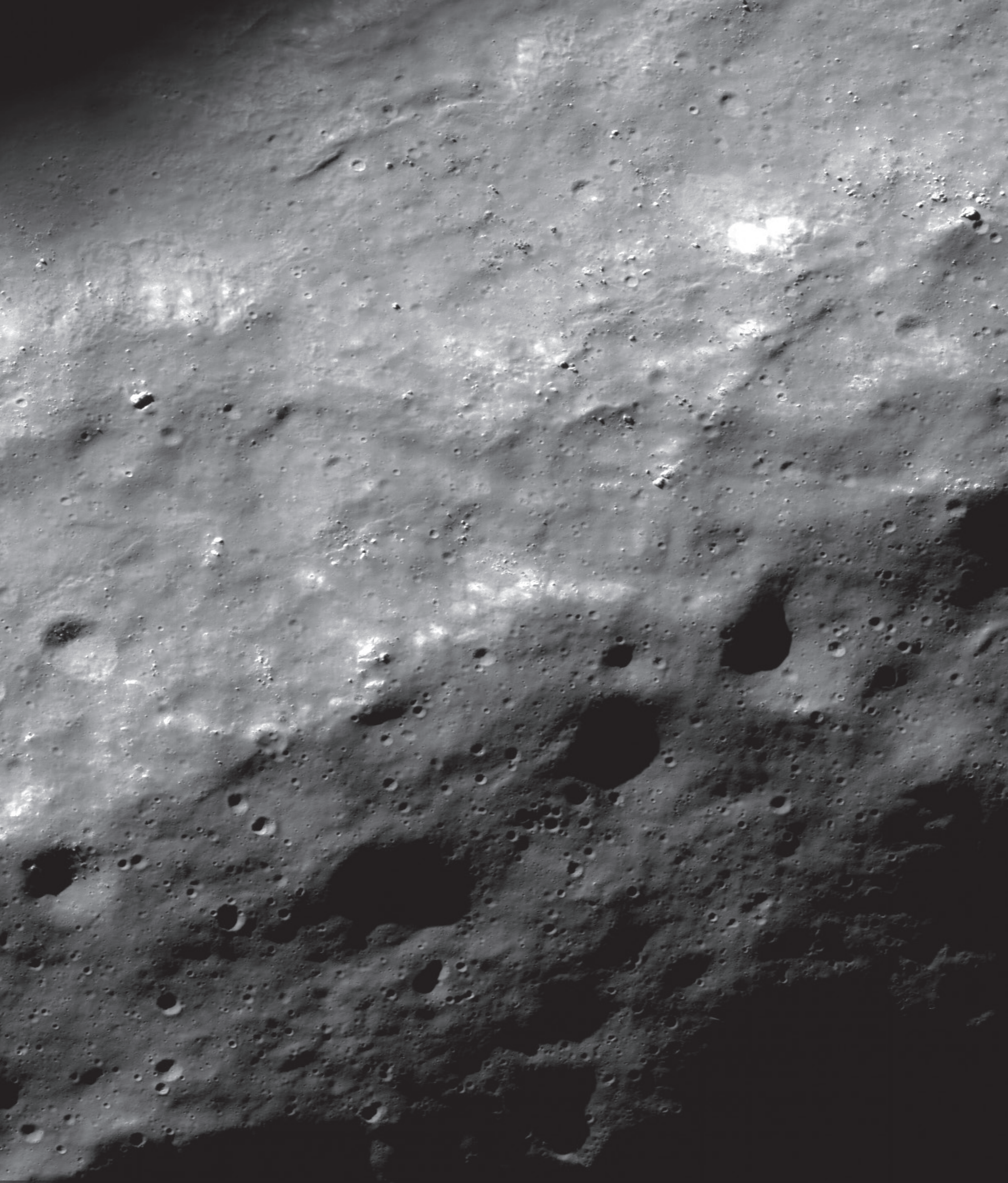
James Spann, Jr., Ex Officio Member
NASA Headquarters

A laboratory physicist by training, Dr. James F. (Jim) Spann, Jr. earned his BS in mathematics and physics from Ouachita Baptist University (cum laude 1979) and his PhD in physics from the University of Arkansas (1985).

Spann is the Heliophysics Division Space Weather Lead at NASA Headquarters. During his 34-year NASA career, he developed and flew in space several auroral UV remote sensing instruments, managed the Marshall Space Flight Center's (MSFC) science research organization, which includes the disciplines of Astrophysics, Planetary Science, Heliophysics, and Earth Science, and served as the MSFC Chief Scientist. He is the author or co-author of more than 70 peer reviewed journal articles, primarily in space physics. He is the Principle Investigator of an international 6U CubeSat mission called SPORT with the Brazilian space agency that will investigate the conditions in Earth's ionosphere, just above its upper atmosphere, that lead to disruptions in communication and GPS signals. He is actively engaged in defining science that exploration at NASA enables, the establishment of a NASA Space Weather Science Application initiative, and coordinating space weather activities with national and international partners. Furthermore, he is heading up the first Lunar Gateway science payload called HERMES that will study the solar wind and enable better space weather forecasting that enhances astronaut radiation protection.

APPENDIX 4

LIST OF WHITE PAPERS SUBMITTED TO THE PANEL



As the Moon heads into southern summer the region around the south pole is better seen by LROC.
One of the many goals of the LRO mission is to improve our cartographic knowledge of the Moon.
Credit: NASA/GSFC/Arizona State University

Appendix 4—List of White Papers Submitted to the Panel

White Paper Number	White Paper Title	First Author Name
2001	Membrane-Based Processing for Exospheric Water-Group Species Captured on the Lunar Surface by Artemis	Californiaa, E.
2002	Debris Scale	Venable, J. C. V
2003	“How to achieve, World Peace.”	McGann, E.
2004	The Origin of Dark Matter - Test Collection at the Moon’s South Pole	Vargas Fèrnandez, E.
2005	Lunar Colony for Large-scale, Multi-generational Lunar Gravity Studies on Mice	Davis, N. A.
2006	White paper for Artemis Science Definition Team	Gonzalez Pizarro, P. G.
2007	Photodocumenting Sample Sites on Artemis Missions to the Moon by Close-Range Photogrammetry	Wells, R. A.
2008	Electromagnetic Sounding of the Lunar Interior from Artemis III	Grimm, R. E.
2009	Elevated dust at the lunar south-pole.	Walker, G. A. H.
2010	Regolith Coring and Long-term Heat Flow Observation through the Subsurface Zone of Ice Stability	Nagihara, S.
2011	Perturbing the Mass and Composition of the Lunar Atmosphere During the Artemis Surface Missions	Levine, J. S.
2012	Lunar Dust and Its Impact on Human Exploration	Levine, J. S.
2013	Ultrahigh accuracy time synchronization technique operation on the Moon	Gurzadyan, V. G.
2014	Young Thrust Fault Scarps as Targets of Opportunity for Exploration and Seismic Hazard Characterization	Watters, T. R.
2015	Artemis Iii Science and Tools Exploration Science for a Near South Pole Crewed Landing.	Schmitt, H. H.
2016	Global Heat Flux Predictions for Landing Sites: Polar Advantages.	Siegler, M. A.
2017	Lunar Heat Flow: Global Predictions and Reduced Heat Flux	Siegler, M. A.
2018	Science Case for Microwave Wavelength Measurements	Siegler, M. A.
2019	Building a lunar network using a long-lived, human-deployed Lunar Geophysical Package (LGP)	Panning, M.
2020	Thermal Infrared Data of the Earth and Lunar Surface (from the Lunar Surface)	Ramsey, M. S.
2021	Human and Robotic Operations Planning Framework for Executing Artemis Lunar Scientific Exploration	Eppler, D. B.
2022	Active Seismic Subsurface Exploration on ARTEMIS III: Exploration and Science Goal	Gulick, S. P.
2023	A proposal for a robotic-human cooperation during NASA Artemis III mission to the Moon’s South Pole	Sommariva, A.
2024	Thorium Assay and Mining Experiment (TAME)	Bruner, W. W.
2025	Marangoni Effect on Molten Lunar Regolith	Dominguez, J. A.
2026	Sample Return of Pristine Lunar Dust to Enable the Design of New Simulants and Activation Protocols for Astronaut Health	Corazzari, I.

2027	*In situ* Toxicological Investigation of the Lunar Dust Reactivity to Design New Simulants and Activation Protocols for Astronaut Health	Corazzari, I.
2028	Hyperspectral Mineral Mapping of the Lunar Surface	Tkaczyk, T.
2029	Moon's vibration modes in the mHz band and the Lunar Gravitational-Wave Antenna	Harms, J.
2030	Seismology on Artemis III: Exploration and Science Goals	Lognonnè, P.
2031	Novel Technologies for Suspension Cultures in Space	Hammond, T. G.
2032	Moon-Drop-Shot	Clark, A. H.
2033	The Importance of Measuring Heat Flux Near the Lunar South Pole	Kiefer, W. S.
2034	SOTERIA: Searching for Organisms Through Equipment Recovery at Impact Areas	Lee, J. A.
2035	Lunar Near-Surface Volatile Sample Return	Aleinov, I.
2036	A Multi-Purpose Landing Site Near Crater Idelíson L	Hiesinger, H.
2037	Study of the Froude Number for Human Locomotion in Space Environment	Ma, O.
2038	Standoff Ultracompact μ-Raman Sensor (SUCR): Search for Polar Ices, Geology and Conduct Human Research	Abedin, M. N.
2039	In-situ chemical analysis of surface material: From in-situ resource utilization to basic lunar science	Riedo, A.
2040	Artemis III EVA Opportunities in the Vicinity of the Lunar South Pole on the Rim of Shackleton Crater	Kring, D. A.
2041	The missing link: connecting remote observations to samples	Honniball, C. I.
2042	Artemis III EVA Opportunities along a Ridge Extending from Shackleton Crater towards de Gerlache Crater	Kring, D. A.
2043	Artemis III EVA Opportunities on the Rim of de Gerlache Crater	Kring, D. A.
2044	Alternative Artemis III EVA Opportunities near de Gerlache Crater	Kring, D. A.
2045	Artemis III EVA Opportunities on the Lunar Farside near Shackleton Crater	Kring, D. A.
2046	Preparing for Artemis III EVA Science Operations	Kring, D. A.
2047	Artemis III EVA Opportunities on Malapert and Leibnitz Beta Massifs	Kring, D. A.
2048	Exploring the Near-Surface at the Lunar South Pole with Geophysical Tools	Schmelzbach, C.
2049	Science Strategy for Understanding Regolith Development and Space Weathering with Artemis III	Denevi, B. W.
2050	Investigations of the effect of material mixing on the spatial distributions of water ice and volatiles in the lunar polar regions	Hirabayashi, M.
2051	Investigating Parameters of Autonomy and Communication in (Cis)lunar Missions to Mitigate the Hazards of Human Spaceflight in Exploration Class Missions	Smithsimmons, A.
2052	Recommended Dust-Plasma Interaction Investigations for Artemis III	Hartzell, C. M.
2053	Understanding the Diverse Particle Environment at the Lunar South Pole Through Simple Sample Collection	Moriarty, D. P.

2054	Whole Earth imaging from the Moon South Pole (EPIC-Moon)	Marshak, A.
2055	Science from an Active Volatile Release Experiment	Prem, P.
2056	On the Importance of Determining Binding Energies of Volatiles on the Moon	Jones, B. M.
2057	Applied Lunar Science on Artemis III in Support of *In Situ* Resource Utilization	Keszthelyi, L.
2058	How Artemis Can Accomplish Major Lunar Exploration Scientific Goals and Objectives: A Sampling Strategy and the “Artemis Rake”.	Head, J. W.
2059	Understanding Rocket Exhaust Effects in Polar Regions During Powered Descent on the Moon	Watkins, R. N.
2060	Quantification and Reduction of Antibiotic-Resistant and Virulent Pathogens on Spacecraft	Thoemmes, M. S.
2061	Artemis Terrestrial Ecosystem Observatory (ATEO)	Huemmrich, K. F.
2062	Using the Lunar Surface as a Platform for Astronomy	Cochran, W. D.
2063	The value of surface-based gravity and gravity gradient measurements at the Moonís south pole with Artemis III	James, P.
2064	Core Samples Recollection of Ice-Bearing Regolith in the PSR¥s of the Moon South Pole	Suarez, J. E.
2065	Neurological, Cardiovascular and Behavioral Consequences of Lunar Exploration using Drosophila melanogaster - Artemis III Mission	Iyer, J. S.
2066	A High-Cadence UV-Optical Telescope Suite On The Lunar South Pole	Fleming, S. W.
2067	*In Situ* 3D Microscopy of Undisturbed Lunar Regolith to Validate Lunar Surface Features	Livengood, T. A.
2068	Uniquely Multidisciplinary Investigations at Amundsen Crater for Artemis III	Runyon, K.
2069	Sample Return of Permanently Shadowed Regions for Space Weathering Investigations	Burgess, K. D.
2070	Enabling Elements for Artemis Surface Science	Neal, C. R.
2071	Geophysical Science on the Surface of the Moon Enabled by Artemis	Schmerr, N.
2072	Portable Magnetic Surveys at the Lunar Surface During Artemis	Richardson, J. A.
2073	Lunar Laser Ranging on Artemis III: Operation and Scientific Goals	Williams, J. G.
2074	Lunar Glass Sampling by the Artemis Crew: Big Science from Small Samples	Zellner, N. E. B.
2075	The Complex Electromagnetic Environment at the Lunar South Pole	Batcheldor, D. P.
2076	Lunar Lettuce Production during Artemis III mission to the Moon’s South Pole	Monje, O.
2077	Next-Generation Geodesy at the Lunar South Pole: An Opportunity Enabled by the Artemis III Crew.	Viswanathan, V.
2078	Next-Generation Lunar Magnetism by Artemis	Tikoo, S. M.
2079	Ground Truth: Testing Theories for the Distribution of Lunar Volatiles	Siegler, M. A.

2080	Temperature Variations within the Moon's Permanently Shadowed Regions	Landis, M. E.
2081	Moon geodesy with radio beacons	Petrov, L.
2082	Characterization of Electrostatically Lofted Dust Environment at High Lunar Latitudes	Petrinec, S. M.
2083	Probing the Geomechanical Properties of the South Polar (Pen)-Umbral Regolith	Bickel, V. T.
2084	Gravitational-Wave Lunar Observatory for Fundamental Physics	Jani, K.
2085	Exploration of lunar dynamic evolution using samples returned from the lunar South Pole	Dygert, N. J.
2086	Application of Biosolids and Wastewater to Lunar Regolith to Jump Start Soil Generation	Posey, J.
2087	Artemis Search for Supernova Isotopes in the Lunar Regolith	Fields, B. D.
2088	Cosmic Ultraviolet Emission-line Survey (CUES)	Morse, J.
2089	Lunar Geophysical Network for Artemis	Bailey, S. A.
2090	A Wide-Field Near-UV Moon Observatory	Barclay, T.
2091	A Survey of Micro Cold Traps at the Artemis III Landing Site to Determine the Rate of Water Delivery to the Moon	Hayne, P. O.
2092	Determining the Earth Radiation Budget	Finsterle, W.
2094	Magic Staff: A tool for frozen volatile hunting	Paige, D.
2095	Lunar Surface Measurements to Inform Both Science and *In Situ* Resource Utilization	McAdam, A. C.
2096	ReconDroid for Artemis-3	Bailey, S. A.
2097	Artemis III Neutron Surface Science	Fuqua Haviland, H.
2098	Characterizing Terminator Space Weather with Artemis III	Fuqua Haviland, H.
2099	SPIKE Miniature Penetrator Probe for Artemis-3	Bailey, S. A.
2100	Dust on the table. Developing lunar regolith for long-term colonization of the inner solar system	Zaharescu, D. G.
2101	Science Objectives for Artemis III Crewed Activities	Stopar, J. D.
2102	Roving Instruments as Part of a Human-Robot team for Sample Return Collection.	Sims, M. H.
2103	Maximizing scientific opportunities through the careful selection, collection, storage, curation, and analysis of samples from the Artemis program.	Gross, J.
2104	Astronaut-Assisted Neutron Mapping	Su, J. J.
2105	NASA Human Service Mission To The ILOS, 2024-2025	Durst, S.
2106	Evidence for a Long-lived Lunar Dynamo Questioned: Robust Definition of the Magnetic History of the Moon	Tarduno, J. A.
2107	Investigations Regarding Subsurface Temperature Profiles at Polar Regions on the Moon	Sehlke, A.
2108	Evaluation of Lunar Regolith Enrichment Techniques for its Usage as Substrate on *in situ* Crop Production	Méndez, Y. N.
2109	Volatile Sample Return by Artemis III	Gerakines, P. A.
2110	Mapping Hydration State and Composition of the Lunar Regolith - An Artemis Science White Paper	Hewagama, T.

2111	SETI from the Lunar South Pole	Michaud, E. J.
2112	Electrostatic Dust Transport Effects on Lunar Regolith Evolution and Dust Hazards	Wang, X.
2113	Science Priorities for Sample Return for Artemis Missions to the Lunar South Pole	Jolliff, B. L.
2114	A Study of Earth's Technosignatures from the Lunar Surface	Elowitz, R. M.
2116	EVA H2O Release: Need for Measurements and Monitoring During Human Exploration of the Lunar Polar Regions	Lee, P.
2117	Connecting the Lunar Surface and Sub-Surface Radiation Environments	Losekamm, M. J.
2118	Photogrammetry to Support Geologic Field Work and Extravehicular Activity (EVA) Operations on the Lunar Surface	Hurtado, J. M.
2119	Detection and Handling of an Electric Discharge on the Moon for Dust Protection, Safe Operation, and Insitu Resource Utilization.	Kletetschka, G.
2120	Chemical Reactivity of *In Situ* Lunar Dust	Rask, J.
2121	Evaluation of Lunar Regolith Potential as Construction Materials Source for Future Artemis Base Camp	Suarez, J. E.
2122	IR Photometric Survey for Transiting Exoplanets around Nearby Stars	Morse, J.
2123	Crew-based Micro-topographic Imaging of the Moon for Science, Exploration, and Safety	Garvin, J. B.
2124	Understanding the 3D Stratigraphy of Icy Regolith Deposits at the Lunar South Pole	Cannon, K. M.
2125	Lunar Poles Rover (LPR): A Search for Hydrated Minerals, Organics, Metals and Light Aggregates in Preparation for ISRU	Trigo-Rodriguez, J. M.
2126	Astrobiology on the Moon: Learning About the Early Earth While Preparing for Mars	Longo, A. Z.

APPENDIX 5

ACRONYMS

Darkness surrounds illuminated peaks between Shackleton crater (rim crest at right) and de Gerlache crater (out of scene left). As lunar days and seasons progress, darkness creeps along this elevated ridge near the south pole. Image width 15 kilometers, NAC M1195011983LR.

Credit: NASA/GSFC/Arizona State University

Appendix 5—Acronyms

A

AAP: Apollo Applications Program
AC: alternating current
ALSEP: Apollo Lunar Surface Experiment Package
ANGSA: Apollo Next Generation Sample Analysis
ASM-SAT: Lunar Exploration Analysis Group (LEAG) Advancing Science of the Moon Report
ARTEMIS: Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun
AU: Astronomical Unit

B

BPS: NASA's Division of Biological and Physical Sciences

C

CAB: Commercial Advisory Board
CAPTEM: Curation and Analysis Planning Team for Extraterrestrial Materials
CK: Contamination knowledge
CLPS: Commercial Lunar Payload Services
CLSE: Center for Lunar Science and Exploration
CRS: coordinate reference frame
CSSD: Contact Soil Sampling Device

D

DALI: Development and Advancement of Lunar Instrumentation
DC: direct current
DEM: digital elevation model
D/H: deuterium to hydrogen ratio
DRA: Design Reference Architecture
DSCOVR: Deep Space Climate Observatory

E

EUV: extreme ultraviolet
EVA: extravehicular activity

F

FAN: Ferroan Anorthosite
FSH: Foundational Surface Habitat
FUV: far ultraviolet

G

Ga: giga-annum, or billion years before present
ge: Earth gravity
GEO-SAT: Lunar Exploration Analysis Group (LEAG) Geology-Geophysics Specific Action Team
GRAIL: Gravity Recovery and Interior Laboratory
GSFC: Goddard Space Flight Center

H

HAB-SAT: Lunar Exploration Analysis Group (LEAG) Habitation Specific Action Team
HEOMD: Human Exploration and Operations Mission Directorate
HERMES: Heliophysics Environmental and Radiation Measurement Experiment Suite
HLS: Human Landing System

I

IAU/IAG: International Astronomical Union/International Association of Geodesy
IMAP: Interstellar Mapping and Acceleration Probe
ISECG: International Space Exploration Coordination Group
ISR: Ice Stability Region
ISRO: Indian Space Research Organizations
ISS: International Space Station

J

JAXA: Japanese Aerospace Exploration Agency

K

KPLO: Korea Pathfinder Lunar Orbiter
KREEP: Potassium, Rare Earth Elements, and Potassium

L

LADEE: Lunar Atmosphere and Dust Environment Explorer
LAMP: Lyman Alpha Mapping Project
LASC: Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) Lunar Allocation Subcommittee
LCROSS: Lunar CRater Remote Observation Sensing Satellite
LDEM GDR: Lunar Orbiter Laser Altimeter (LOLA) digital elevation model (DEM) gridded data record
LDEP: Lunar Discovery and Exploration Program
LEAG: Lunar Exploration Analysis Group
LEAM: Lunar Ejecta and Meteorites experiment
LEND: Lunar Exploration Neutron Detector
LER: Lunar Exploration Roadmap
LExSWG: Lunar Exploration Science Working Group
LGCWG: Lunar Geodesy and Cartography Working Group
LMO: Lunar Magma Ocean
LOLA: Lunar Orbiter Laser Altimeter
LSITP: Lunar Surface Instrument and Technology Payloads
LPI: Lunar and Planetary Institute
LRO: Lunar Reconnaissance Orbiter
LRO NAC: Narrow Angle Camera
LRO WAC: Wide Angle Camera
LTV: Lunar Terrain Vehicle

M

M3: Chandrayaan-1 Moon Mineralogy Mapper
MATISSE: Maturation of Instruments for Solar System Exploration
MAN: Magnesian Anorthosite
MI: SELenological and Engineering Explorer (SELENE) Multi-band Imager
Myr: million years

N

NAC: NASA Advisory Council
NESC: NASA Engineering and Safety Center
NEXT-SAT: Lunar Exploration Analysis Group (LEAG) Next Steps on the Moon Report
NPLP: NASA Provided Lunar Payloads
NRC: National Research Council

P

PDS: Planetary Data System
PEL: Permissible Exposure Limit
PICASSO: Planetary Instrument Concepts for the Advancement of Solar System Observations
PRISM: Payloads and Research Investigations on the Surface of the Moon
PSR: permanently shadowed region

R

RE: Earth radius (radii)
RTG: Radioisotope Thermal Generator

S

SBE: surface boundary exosphere
SCEM: National Research Council (NRC) Scientific Context for the Exploration of the Moon report
SDT: Science Definition Team
SELENE: SELenological and Engineering Explorer
SIDE: Suprathermal Ion Detector Experiment
SIMPLEX: Small Innovative Missions for PLanetary EXploration
SLS: Space Launch System
SMD: Science Mission Directorate
STM: Science Traceability Matrix
STMD: Space Technology Mission Directorate
SNAP: Systems for Nuclear Auxiliary Power
SPA: South Pole-Aitken Basin
SSERVI: Solar System Exploration Virtual Institute
SVS: Goddard Space Flight Center (GSFC) Scientific Visualization Studio

T

TC: SELenological and Engineering Explorer (SELENE) Terrain Camera
THEMIS: Time History of Events and Macroscale Interactions during Substorms
TMC: Chandrayaan-1 Terrain Mapping Camera
TOP-SAT: Lunar Exploration Analysis Group (LEAG) Themes, Objectives, and Phasing Specific Action Team
TRL: Technology Readiness Level

U

USGS: United States Geological Survey
UV: Ultraviolet

V

VIMS: Cassini Visible and Infrared Mapping Spectrometer
VIPER: Volatiles Investigating Polar Exploration Rover
VSE: Vision for Space Exploration
VVM-SAT: Lunar Exploration Analysis Group (LEAG) Volatile Viability Measurement Specific Action Team

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