Artemis III Science Definition Team Report

The Beginning of a Bold New Era of Human Discovery

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Special Introduction to the Interim Report of the Artemis III Science Definition Team (SDT)

This is a DRAFT report that reflects the status of the SDT deliberations at this time, and as such some sections are still subject to further deliberation by the SDT. The Executive Summary (Section 1), Cross-Objective Commonality (Section 6), and Findings and Recommendations (Section 10) sections will be updated to incorporate aspects of community feedback after the public comment period closes. Referencing, Appendices, and general typesetting are incomplete at this time, but will be finalized likewise.

1. Executive Summary

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2. Introduction

The Moon, with its abundant resources and vast unexplored regions, is the most attainable and useful near-term target for future human exploration. The experience gleaned from the Apollo expeditions – collectively, the field work performed by the astronauts on the surface and the samples they brought back – is the cornerstone upon which five decades of achievement in planetary science is built. Nonetheless, numerous important science questions about the Moon remain, many with implications for the entire Solar System.

In the 21st century, there has been a resurgence of international interest in the Moon, including the Kaguya mission by the Japanese Aerospace Exploration Agency (JAXA); the Chandrayaan-1 mission by the Indian Space Research Organizations (ISRO); four Chinese missions: 2 orbiters (Chang'E-1 and -2) and two landed missions with rovers (Chang'E-3 and -4); as well as four NASA missions: 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). Breakthrough discoveries from Chandrayaan-1, LRO, and LCROSS – especially those regarding volatiles – have reinforced the Moon's status as a cornerstone of planetary science.

Taken collectively, the results from these missions have shown that the Moon is a far more valuable, and far more interesting, destination for future exploration than was perceived even during the Apollo era. The Moon is not a barren and dormant world – it is a resource-rich world with unparalleled opportunities for scientific discoveries and commercial activity (Keller et al., 2016; LEAG, 2016, 2017a,b, 2018). Results from recent lunar missions have only increased the necessity for a comprehensive program of lunar exploration and utilization that will drive economic growth, promote international collaboration, and enable significant scientific advances.

Space Policy Directive 1, "Reinvigorating America's Human Space Exploration Program" states that the United States will:

> *Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations.*

The National Space Council expanded on this directive at the fifth meeting of the National Space Council on March 26, 2019, in Huntsville, Alabama, and adopted this recommendation:

> *Consistent with the overall goals of SPD-1, the United States will seek to land Americans on the Moon's South Pole by 2024, establish a sustainable human presence on the Moon by 2028, and chart a future path for human Mars exploration. NASA's lunar presence will focus on science, resource utilization, and risk reduction for future missions to Mars.*

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 first human mission to the Moon in the 21st Century, the Artemis III mission. These prioritized science activities were deemed essential information needed on an expedited basis to inform the ongoing Human Landing System development activities underway in the Human Exploration and Operations Mission Directorate (HEOMD) . Once established, the Science Definition Team proceeded to execute a complete assessment of science objectives for the Artemis III mission and implemented a comprehensive community engagement strategy. This report presents the outcome.

2.1 The Artemis Science Plan

NASA's Science Mission Directorate is leading the formulation of the Artemis program science strategy, and has developed science objectives for the Artemis program, defined here to include all Artemis missions up to and including activities at the Artemis Base Camp. These science objectives were published in [NASA's Lunar Exploration Program Overview] and 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 are driven by established community priorities, including those in the 2013-2023 Planetary Decadal survey (NRC, 2011), the 2007 National Research Council 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), and the 2018 LEAG Advancing Science of the Moon Report (ASM-SAT, 2018). These reports all outline the value of a robust lunar exploration plan that holds significant promise for addressing 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.

Investigations designed to accomplish these objectives will uphold all NASA research standards, including competitive selections and open data policies. NASA intends to foster competitive research by creating lunar investigation opportunities associated with the Artemis program, which will be conducted according to all NASA research standards, including competitive selections 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.

The nature of science is iterative. Artemis crews will reach the lunar surface and conduct field work and fundamental research that 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 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 only be the first in this new era of sustained exploration. Artemis III will not answer every open science question about the Moon, but based on the consensus expressed in the existing community documents summarized above and fully developed in this SDT report, it is expected that discoveries made on the Moon will have dramatic impacts on our understanding of the entire Solar System.

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 the lunar far side. Creating a pathway to advance low-technology readiness level (TRL) components and sensors is also part of the Artemis science implementation strategy for human and human-robotic science.

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 bold new era of human discovery. The Artemis III mission will be the first steps on a bold, and inspiring, journey of human discovery.

3. Overview of Guiding Community Documents and Additional Community Input

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) (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. However, beginning in the early 1980s, the realization that the National Space Transportation System could be used to mount human lunar surface missions caused active planning for lunar surface missions to resume (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];
- The Vision for Space Exploration (2004);
- 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 GEO-SAT (2005);
- LEAG HAB-SAT (2005);
- LEAG TOP-SAT (2005);
- Proceedings of the Conference on Astrophysics Enabled by the Return to the Moon (2006)
- The Global Exploration Strategy: The Framework for Coordination (2007);
- NASA Advisory Council Workshop on Science Associated with the Lunar Exploration Architecture, Tempe, AZ (2007);
- National Research Council: The Scientific Context for Exploration of the Moon (2007);
- The NEXT Workshop in Washington DC, August 2010;
- Vision and Voyages for Planetary Science in the Decade 2013-2022, NRC (2011) [2013-2022 Planetary Decadal Survey];
- LEAG Robotic Campaign Analysis Letter;
- The LEAG Lunar Exploration Roadmap (2012-Present);
- The LEAG-ISECG Volatiles Special Action Team;
- The LEAG-ISECG Volatiles Special Action Team 2;
- The LEAG Volatile Viability Measurement Special Action Team (VVM-SAT);
- Next Steps on the Moon Specific Action Team (NEXT-SAT);
- Advancing Science of the Moon Specific Action Team (ASM-SAT);
- Global Exploration Roadmap v. 3.1 (2020); and
- Community white papers solicited for this SDT.

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 have 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, four reports have been deemed particularly important. Each has 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 plan 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. An ambitious human lunar exploration program was outside the scope of the 2003 Planetary Science Decadal survey and the SCEM Report was designed to outline a credible program of scientific investigations enabled by the early Constellation Program sortie missions and uncrewed precursor missions. 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 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 is led by a Chair and an Executive Committee who serve as the principal representatives of the United States lunar exploration community to stakeholders, including NASA and the international community. 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 are intended to represent consensus from the lunar exploration community. For the purposes of the Artemis III SDT, two LEAG study activities were deemed particularly relevant and used to inform SDT deliberations.

The LEAG Lunar Exploration Roadmap (hereafter, US-LER) is the cohesive strategic plan for using the Moon and its resources to enable the exploration of all other destinations within the Solar System by leveraging affordable investments in lunar infrastructure. The US-LER was initially released in 2012 and is a living document developed over four years through a comprehensive community-based process, building most specifically off of the results of the 2007 NASA Advisory Council Workshop on the Lunar Exploration Architecture. 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 US-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. While 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 four documents provide a comprehensive assessment of priorities resulting from extensive community participation and established for any lunar exploration program. The Artemis III SDT was tasked with using these four 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 Artemis SDT process. This input was used to strengthen and broaden the Science Traceability Matrix (STM) and integrated report:

1. Community input was solicited early through the submission of Artemis III white papers on science objectives for the Artemis III mission, which were used by the SDT while drafting the Science Traceability Matrix (STM). A list of submitted white papers can be found in Appendix 4.
2. Additional targeted input was solicited from community groups such as the Lunar Exploration Analysis Group (LEAG), Curation and Analysis Curation Team for Extraterrestrial Materials (CAPTEM), CAPTEM Lunar Allocation Subcommittee (LASC), and Solar System Exploration Research Virtual Institute (SSERVI) teams Principal Investigators during the process of STM preparation to ensure that he document captures the science priorities from the community. A summary of science topics highlighted by this community input can be found in Appendix 2.
3. A targeted subgroup of scientists with broad or specific lunar science experience were asked to provide perspectives based on their individual, specialized scientific background and topical knowledge to ensure that key science areas were discussed, captured, and addressed in the STM and subsequent report. Such science topics are also included in Appendix 2.

4. Artemis Program and Architecture Summary

The Artemis program is a collective effort led by NASA to explore more of the Moon than ever before, 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 powerplants.

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 outlined in the National Space Council's "A New Era for Space Exploration and Development," 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. This will be accomplished through extraterrestrial operations, such as manufacturing and mining, as well as conducting cutting-edge lunar science, all of which will enable America and our 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 the lunar south pole) as the location for the Artemis III landing site and the subsequent Artemis Base Camp reflects this broad, all-of-government approach to executing a sustained program of lunar exploration. This approach provides significant economic and operational 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 has the effect of producing areas which 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., 2001, Nozette et al., 1996, Li et al., 2018). As has been noted since 1996, the economic potential of these resources is vast, and are of great strategic interest to the United States (e.g., Spudis, 2016). When the grade and tonnage of these volatile deposits are characterized, a cislunar economy will be created, providing significant cost reductions for lunar surface logistics and resupply efforts (Spudis and Lavoie, 2011; Kutter and Sowers, 2016; Sowers and Dreyer, 2019; Cannon, 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 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. While outside of the scope of the Artemis III SDT, 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 (Coombs and Hawke, 1991; 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, 2007; Vision and Voyages, 2011;Lunar Exploration Analysis Group, 2016, 2017, 2018; Jawin et al., 2018; 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. 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 an important consideration that will 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 prepositioned.

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 a 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 of a series of missions to construct 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 more defined, NASA will begin to prioritize specific science activities for the surface expedition crew. Each EVA will begin with tool selection and preparation for the day's investigations. The day will end with a decontamination process to reduce the amount of lunar dust that may be tracked from the spacesuits into the crew cabin.

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 STM introduced in this report.

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 geological 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).

5. 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 our guiding community documents, and prioritizes *Investigations* under some (but not all) of the Goals, 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.

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 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

The SDT was charged with expanding upon these specific Objectives. It chose to map science Goals (areas of research) and Investigations (specific activities undertaken to address goals) to them (Table 1, appended to end of document). The SDT then undertook prioritization at the science Investigation level. Each investigation was ranked on 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 do-able is the investigation by Artemis III mission). Both the traceability and the prioritization drew on the community-submitted white papers and previous community-developed documents (section 5.1). In large part, traceability 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, 2007) is still very much relevant. Since no significant 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 Goals and Investigations trace more directly to more recent documents such as the VVM-SAT and ASM-SAT.

In keeping with the nature of this Interim Report, the SDT has not yet further ranked any investigation over any other. We anticipate community input into the prioritization. The Science Objectives and Goals are further discussed in the following sections, along with each of the highly-ranked investigations.

5.1 Objective 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 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 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. <u>Formation of the Earth-Moon system.</u> 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. The 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 the Earth and the Moon and how conditions for life may have evolved.

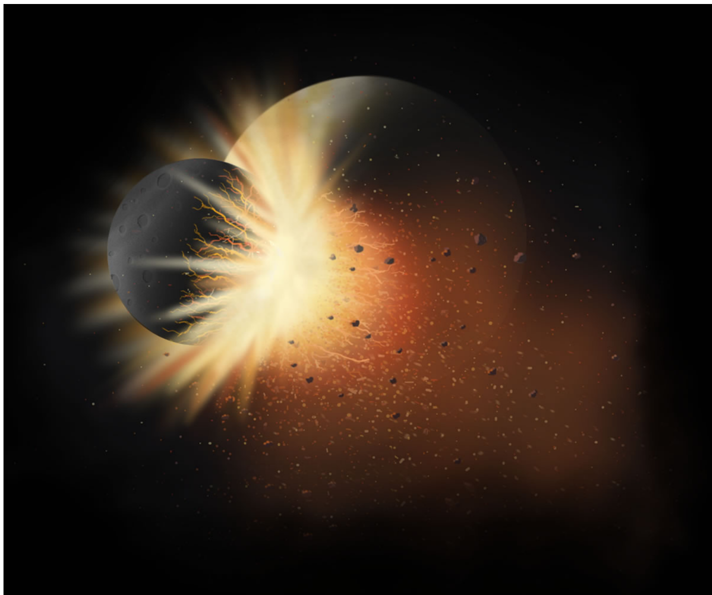

Figure 5.1.1: Moon-forming impact. The leading hypothesis for the origin of the Moon involves a huge collision between the Earth and a planet half its size. That concept is often called the Giant Impact Hypothesis. This hypothesis suggests some of the colliding material was added to the Earth, while a large fraction of the impact debris went into orbit around the Earth. The orbiting material then accreted together to form the Moon. The collision and subsequent accretion of the Moon occurred 4.5 billion years ago. Reproduced from Barnes et al., (2012).

<u>Investigation 1a-1.</u> 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 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), and evidence in remote sensing data 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 previously unsampled 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 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.

<u>Investigation 1a-2.</u> Constrain the physicochemical conditions and processes that operated at the surface of the lunar magma ocean

The formation of pure igneous anorthosite rocks during planetary 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 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.

<u>Investigation 1a-3.</u> 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, 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.

Goal 1b. <u>Planetary differentiation and evolution: Formation of a magma ocean, crust, mantle, and core.</u> 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 composition, as well as the pressure and temperature conditions during this separation, are reflected in the Moon's current chemistry, structure, and dynamics.

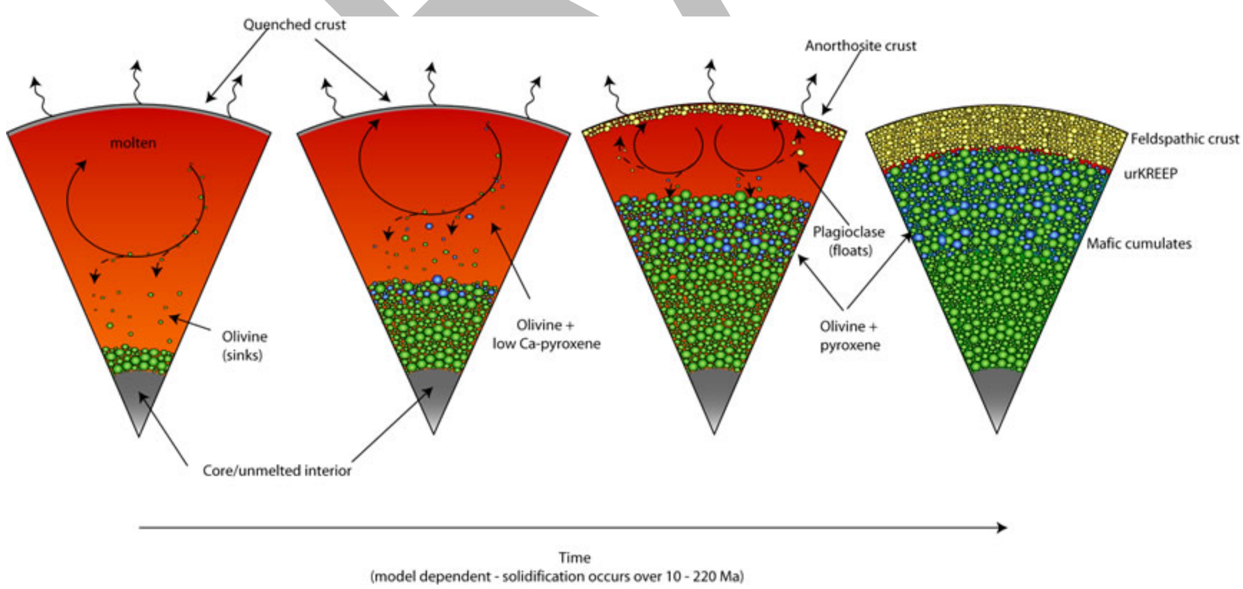

Figure 5.1.2: Lunar magma ocean crystallization. Shortly after accretion, a large proportion of the Moon was molten, referred to as the lunar magma ocean (LMO). Fractional crystallization of the LMO is currently the best model to account for known lunar lithologies and begins with crystallization of 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). Reproduced from Barnes et al, (2012).

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 limited by uncertain single-point 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 are 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 large 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) produces 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, 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 and is critical to compare to ground truth orbital data, to put into context our lunar meteorite collections, and for our understanding of lunar planetary differentiation and the planetary differentiation of other planetary bodies.

<u>Investigation 1b-2.</u> 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 abundances 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 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 geophysics 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.

<u>Investigation 1b-3.</u> Inventory, relationships, and ages of nonmare rocks

Rocks in the lunar crust shed light on the process 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, 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 to determine the sequence and structure within the crust and reconstruct crustal evolution in space and time.

Goal 1c. <u>Volcanism: Partial melting, eruptions, flow sequence and compositions.</u> 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 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. This 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. <u>Tectonism: deformation of the crust and thermal history.</u> 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). Most tectonic structures are located on the near side and are spatially associated with mare basins, though recent studies have indicated that tectonic structures are globally distributed (e.g., Nahm et al., 2018). Wrinkle ridges are almost exclusively located within mare basins, whereas lobate scarps and graben are found in both mare and highlands regions. As surface expressions of thrust faults, lobate scarps require the largest amount of stress to form and experience slip. These structures are thought to have formed in part as a response to compressional stress resulting from late-stage global cooling and contraction, 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. 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. <u>Impact processes: basins and craters, mixing of the crust, crustal stratigraphy.</u> 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 the original crust rocks and obscured the original distribution of the products of primary differentiation and subsequent geologic activity.

Goal 1f. <u>Regolith processes and weathering.</u> The Moon is a natural laboratory for regolith processes and weathering on anhydrous bodies. Regoliths, exemplified by the lunar regolith, form on airless bodies of sufficient size to retain 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 modification and alteration products 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 (Figure 5.1.3). Knowledge of the processes that create, modify, and transport the lunar regolith is essential to understanding the compositional and structural attributes of other airless planet and asteroid regoliths.

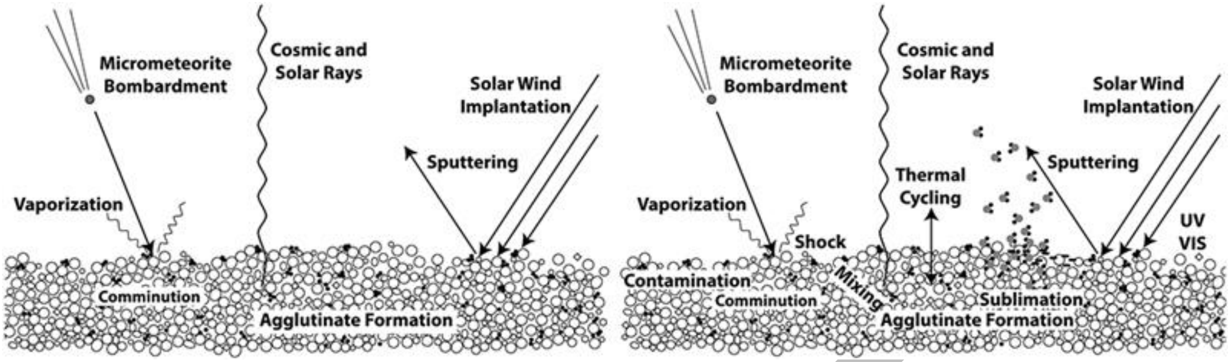

Figure 5.1.3: The complex array of processes involved in space weathering of airless bodies. Typical soils are particulate but heterogeneous in composition. (left) Dominant processes affecting the surface of the Moon at 1 AU (after Noble, 2004). (right) The broad range of surfaces processes now believed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

Investigation 1f-1. Determine physical properties of regolith at diverse locations of expected human activity

Owing to the importance of regolith on the exploration of the lunar surface and on lunar resources, developing a thorough understanding of regolith properties (including chemistry, mineralogy, physical properties, volatile content and storage mechanisms, and regolith formation) is critical to taking advantage of this critical 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.

5.2 Objective 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 to exist in extremely cold permanently shadowed craters near the poles for several decades. 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), 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), 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 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).

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 M^3 (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 globally at the cooler high latitude regions and lesser amounts at lower latitudes across the Moon. Recently, statistical analysis of low M^3 signal at the poles enabled small amounts of water ice to be directly detected in the shadowed regions (Li et al. 2018).

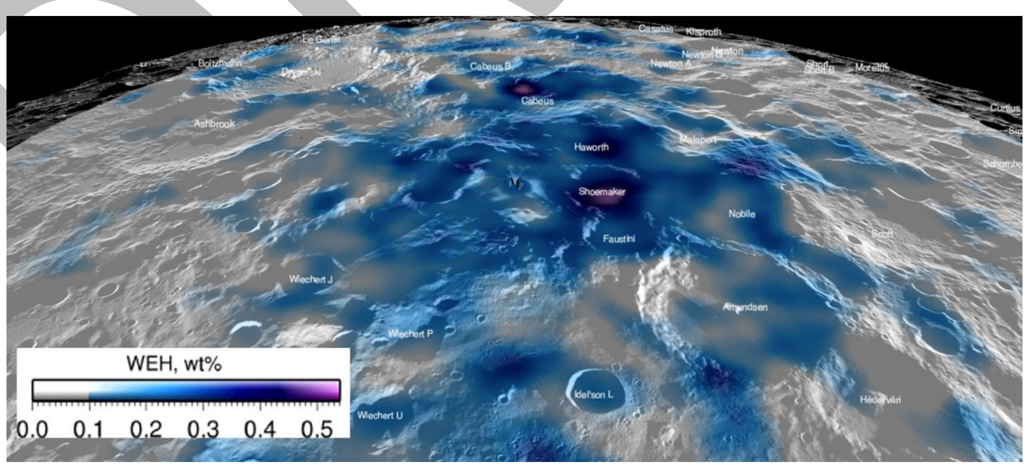

Figure 5.2.1: LEND polar water equivalent hydrogen map. Perspective view of the estimated abundance of water equivalent hydrogen around the lunar south pole. Map from Sanin et al. (2017) and overlain on LROC WAC mosaic in QuickMap (https://bit.ly/2T46NdO).

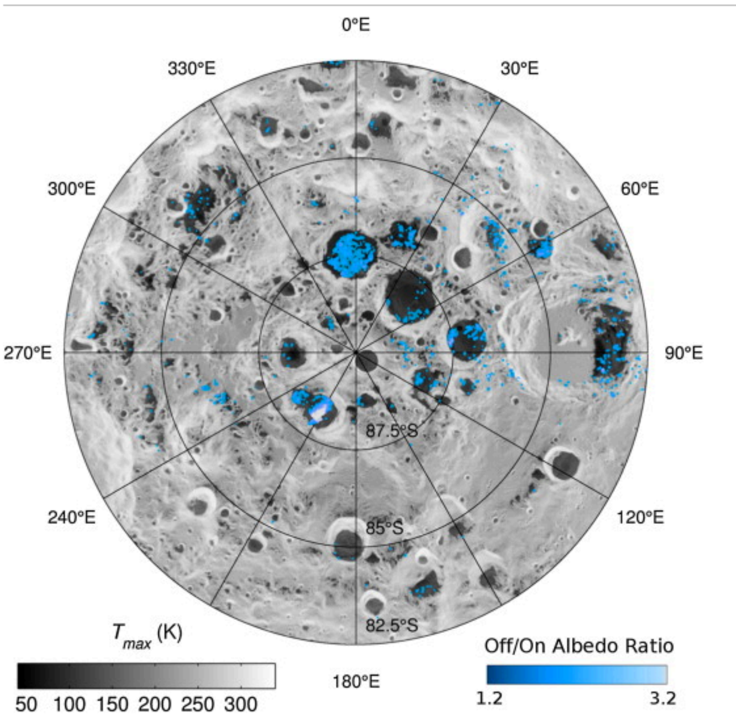

Figure 5.2.2: LRO LAMP surface water ice map. Location of anomalous LRO LAMP UV albedo consistent with water ice. Off/on albedo ratios between 1.2-4.0 are consistent with water ice concentrations of ~0.1-2.0% by mass. Patchy exposures of pure water ice mixed with dry regolith may increase water ice abundances up to ~10%. Reproduced from Hayne et al. Evidence for exposed water ice in the Moon's south polar regions from the Lunar Reconnaissance Orbiter ultraviolet albedo and temperature measurements (2015).

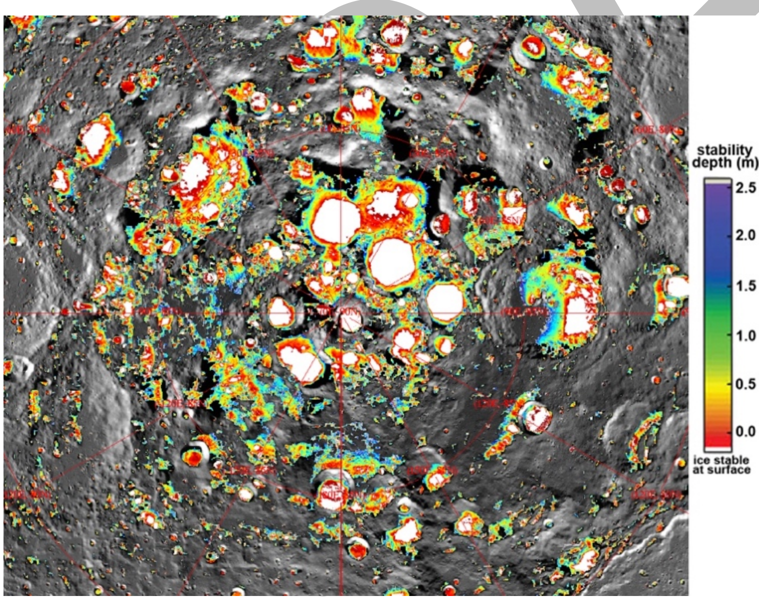

Figure 5.2.3: LRO Diviner current model polar ice stability map. Model-calculated depths at which water ice would be lost to sublimation at a rate of less than 1 kg m^{-2} per billion years (Paige et al. 2010). The white regions define the locations where water ice can currently be cold-trapped on the 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 LROC QuickMap web tool.

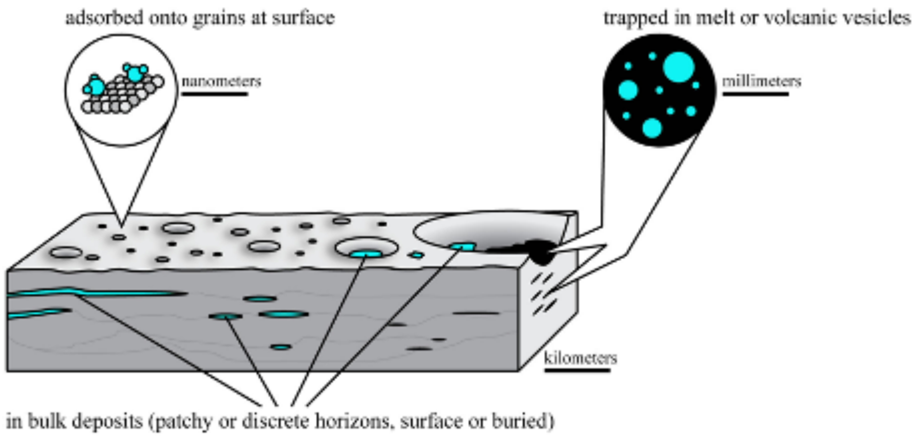

Figure 5.2.4: Possible forms and scales of lunar polar volatile deposits. A schematic diagram illustrating the potential distribution and scale of volatile components across the surface and trapped near or below the surface at the lunar poles (e.g., adsorbed molecules, grains with altered or trapped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

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 the Dry (warmest and most sunlit) region followed by the Deep, Shallow, and then Surface (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 duration 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. <u>Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and with depth) of the volatile component in lunar polar regions</u>. 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 the 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 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.

<u>Investigation 2a-4.</u> Speciation of surface hydrogen.

Data from the Lunar Prospector and LRO missions has 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 collected 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.

<u>Investigation 2a-5.</u> 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.

<u>Investigation 2a-6.</u> Spatial distribution of subsurface hydrogen.

Data from the Lunar Prospector and LRO missions has 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.

<u>Investigation 2a-7.</u> 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 only exist 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 complimentary 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-3. 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, O^{18}/O^{16}, 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 diurnal and seasonal 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 which will thereby improve 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.

Little quantitative data exists 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-3. 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 collected 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. Document and understand the impact of exploration activities on the lunar volatile record. Activity on the lunar surface (both robotic and human) will inevitably alter the current natural state of the surrounding region. 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 2e-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 Objective 3: Interpreting the Impact History of the Earth-Moon system

The heavily cratered surface of the Moon provides an exceptional historical 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., 2008; Le Feuvre & Wieczorek, 2011; Schmedemann et al., 2014). However, this crater counting calibration currently depends on the calibration of the returned Apollo samples that were collected in a narrow nearside equatorial zone and may not be 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 of significant scientific importance. In particular, the impact rate during the period >3.9 Ga remains poorly constrained by existing samples. 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 has 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. 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 relics of impactor material to be identified are necessary for understanding these important themes.

Goal 3a. <u>Test the cataclysm</u>. 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 on 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.

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 the 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 require obtaining samples and dating additional Pre-Nectarian or Nectarian basins.

Notably, the south polar region above 84° is 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 reasonable chance that SPA impact material was transported into the region as ejecta, as well as through later impact events. If this is the case, it may be recognizable on the basis of SPA's inferred geochemical differences with background highlands. Because Artemis III's current architecture does not enable landing at a location identified by the community as having a high probability of having impact materials clearly attributable to SPA or another early specific basin, this subgoal was not prioritized as a key investigation. However, that does not obviate this goal's importance, and the samples returned from the landing site may ultimately help address this goal4

Goal 3b. <u>Understand changes to Earth-Moon bombardment in the post-basin era</u>. 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.

Goal 3c. <u>Understand the impact history of the landing site</u>. 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. 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.

<u>Investigation 3c-1.</u> Determine the sequence of individual craters and basins that influence local, regional, and global stratigraphy at the Artemis III landing site.

This investigation encompasses field geology and geologic mapping; coring, trenching, and/or geophysical measurements to establish regolith stratigraphy; determination of the provenance of boulders and/or outcrops; and, critically, sample analyses. Sample provenance investigations would be required to determine the origin of collected material, but rake samples would likely contain some material from many impact events that can aid our understanding of the magnitude, timing, and impact flux on the Moon over time. This investigation requires the collection of a diverse set of samples in order to adequately capture a variety of local and regional impact events. The information gathered in this investigation may also address or partly address Goals 3a and 3b.

5.4 Objective 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 extra-galactic 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. <u>Understand the history of the Sun, including the composition and flux of the solar wind.</u> 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 scientific 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. <u>Understand the record of solar energetic particles, cosmic rays, gamma-ray bursts, and supernova.</u> 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, building of 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 Objective 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. 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. In particular, the lunar surface offers unique opportunities for long wavelength radio astronomy from the radio-quiet far side of the Moon.

The LEAG Lunar Exploration Roadmap offers a significant amount of additional details capturing the variety and value of observing the Sun, Earth, and Universe from the unique vantage point of the lunar surface. One of the themes that recurs in the LER is the value of emplaced infrastructure towards enabling observations of this type. As the first mission of a series of missions, it is anticipated that the value of Artemis III towards the below Goals will lie in scouting for reasonable sites to deploy relevant investigations and partnering with the relevant science communities to realize them.

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. 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. 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, studies of solar wind access such as in the lunar wake and at polar craters, and studies of lunar crustal magnetism, particularly those that may limit solar wind access to the surface possibly affecting space weathering and albedo. 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; Stubbs et al., 2007a). 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 affects occurring at the local level like surface secondary emission characteristics. 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 RE is about four times closer to the Earth than 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 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.

5.6 Objective 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 (LER, 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. 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 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.

5.7 Objective 7: Investigating and Mitigating Exploration Risks

The exploration of the Moon represents an exceptional opportunity to investigate the response of hardware, humans, and other organisms to a new and extreme environment. For the first time in five decades we will be able to study how humans respond to a reduced gravity environment for extended periods of time. Despite the relatively short duration of Artemis III on the lunar surface (six days), this exploration represents an excellent opportunity to commence investigations into how living systems respond to the lunar environment (*e.g.*, 1/6th g_e, deep space radiation) and how the space environment (both lunar dust and electrodynamics) shape the area explored by Artemis III. Such exploration helps prepare for both longer duration lunar missions and eventual missions to Mars. Both 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 12 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 possible initial opportunities afforded by Artemis III which begin to address the goals. Only three of the goals were deemed by the SDT to be addressable in a meaningful way by the Artemis III mission.

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). The biological science that could 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 and radiation on the biological systems (including those of humans). Lacking a long duration stay on the Moon, as well as dedicated research space for experiments, Artemis III’s response to investigating and mitigating exploration risks to humans is limited yet is still a valuable first step to understanding how biological systems respond to the lunar environment. The first ten goals of this objective entail the study of human, biologic, and plant systems over the long term.

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 reduced gravity, isolation, and, radiation environment may impact human and non-human life forms in as-of-yet unknown ways. Long-duration exploration of the Moon may provide a more robust measure of how life reacts to this environment. The Artemis III mission may provide the initial bench-mark data for human response to this environment.

Goal 7b. Study the key physiological effects of the combined lunar environment on living systems and the effect of pharmacological and other countermeasures. The response of biologic systems to “countermeasures” will certainly inform how future explorers will react in unique environments such as the Moon. Over the six days of Artemis III an initial baseline of data may be acquired from the crew, and simple experiments initiated on the first day on the lunar surface may provide a preliminary datapoint on the human response to the lunar environment, but only when the final concept of operations for the mission are developed will the space medicine community be able to define what may be gleaned from the mission.

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 relative compared to the Apollo J-missions will provide an initial perspective on how the human body reacts. Deconvolving the response to multiple days in micro-gravity may necessitate measurements performed on the lunar surface in the crew cabin, however this will need to be fit into the as-of-yet undefined timeline of the mission while on the lunar surface.

Goal 7d. Study the effects of lunar radiation on biological model systems. The short surface stay of the Artemis III crew may not allow for an appropriate response to the lunar radiation environment, which thus far has been measured with great accuracy by the CRaTER instrument on the LRO mission. Therefore such experiments for either this initial mission or any future long-term missions

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 III 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 as it may be). However, to address multigenerational processes may not be adequately resolved in a short surface stay.

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. For the first time since December 1972 we will have humans transition from 1 g_e, to ~0 g_e, to 1/6th g_e, and back. However, the short duration spent out of 1 g_e may preclude the return of valuable insight into this process.

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, this first mission may provide an opportunity to examine how taste changes in the lunar environment, and therefore provide the initial supporting data for this long-term experiment. In this example, as with several others in this objective, while the main science question may not be directly addressed, the opportunity to bound the problems with initial data are there.

Goal 7h. Evaluate the use and effectiveness of model plants in ecological life support systems. As with prior goals, there may not be sufficient time to directly grow and harvest plants during the Artemis III surface mission. Therefore, any precursor measurements or data may need to be identified so that future, longer duration missions, may begin to 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 the raw material, in the form of lunar regolith, to enable the investigation of how microbes and plants respond to lunar regolith. The LER defines two science goals, "Study effect on microbes of long-duration exposure to the lunar environment" and "Assess effect on plants of long-duration exposure to the lunar environment" that benefit from the availability of new regolith samples. Specifically, the science questions "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 to South Polar regolith by way of studies performed on the Earth using such regolith samples, perhaps even regolith samples specifically collected for use in future biologic studies (provided the collection of such samples does not negatively impact crew operations). One could also imagine a simple study started in the crew cabin where soil is added to an experiment pre-packaged with seeds to initiate growing on the lunar surface and continued during the return trip to Earth.

Goal 7k. Understand lunar dust behavior, particularly dust dynamics and Goal 7l Understand lunar electrodynamics are both goals that are fundamentally enabled by the exploration of the lunar south polar region. With the nearly constant movement of the lunar terminator in the cis-polar environment there exists a dynamic between illuminated, un-illuminated, and permanently shadowed regions that can begin to be understood during Artemis III. The interplay between dust and the lunar regolith makes constraining the dust environment (as it exists) an important part of understanding the evolution of the regolith as well as any possible movement of material. Understanding the dust 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.

To constrain these processes will require the emplacement of experiments, some of which will need to operate after the crew departs the surface. A passive system to sample 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 dust transportation (on a short timescale). 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.

Investigation 7k-1. Understand the properties of electrostatic lofting and levitation.

Investigation 7k-2. Dust-Plasma Interaction on the Surface & Exosphere of the Moon.

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 reduce likelihood of mission success and impact crew safety. 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 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.

Investigation 7m-2. Provide real-time environmental information relevant to daily lunar 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 covered in lunar dust as he was particularly eager to get close to the surface to get close-up views of the samples he collected.

6. Cross-Objective Commonality

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7. Enabling Capabilities

7.1 Power

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.

Several of the Investigations prioritized in this report would be maximally enabled by a long-lived power source for deployed experiments. Beginning with Apollo 12, The Apollo Lunar Surface Experiments Packages (ALSEP), consisting of a series of geophysical and environmental monitoring instruments connected to a central base station, were powered by SNAP-27 Radioisotope Thermal Generators (RTG) that provided 70 Watts of continuous power and permitted night survival and operations (Figure 7.1.1).

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.

Feeding forward to future Artemis missions, a long-lived power source would be necessary 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.

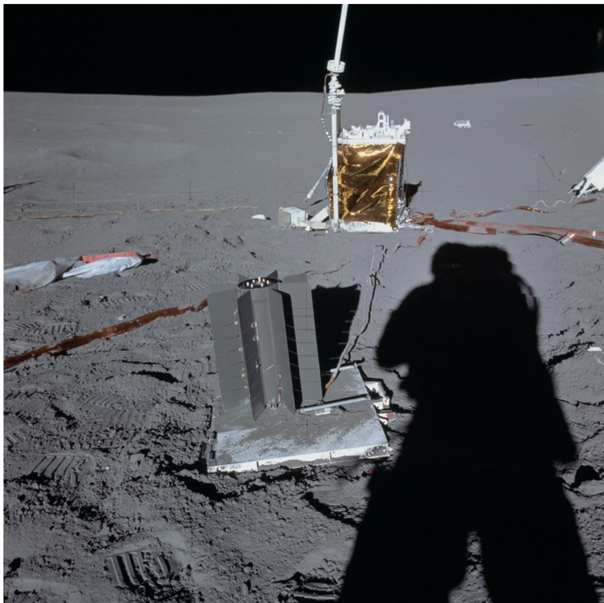

Figure 7.1.1: Apollo Image AS14-67-9366. Astronaut Alan Shepard's shadow over the Apollo 14 SNAP-27 RTG, as he photographed the deployed Apollo Lunar Surface Experiments Package. The central base station, which transmitted data from the instruments back to Earth, is visible in the background with its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

7.2 Pre-deploy

At the time of writing of this report, the downmass capability of the HLS is not finalized. Existing mass allocations expected to be available natively 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 external stakeholder community in our Guiding Documents. Our recommended program (Section 13) 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 4), but the ability to pre-deploy science assets using CLPS landers 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. These could include:

- Detailed survey of the human landing zone prior to human arrival
- Provide independent precision navigation aids for landing
- Third person video documentation of historic human return
- Enable contingency extension of surface stay time with extra consumables and spares
- Early robotic exploration to focus and accelerate human exploration
- 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 DRM 5.0 (Drake et al., 2009).

7.3 Mobility

The Artemis III mission does not, as presently formulated, include availability of an unpressurized lunar rover. 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. The 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 enabling a range of scientific activities, and 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.

8. Cartographic Recommendations

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 Kaguya provide a comprehensive view of the modern 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 frame (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 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/Kaguya 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 such as those from 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), Kaguya 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) have not been tied to each other or controlled to a single geodetic lunar coordinate reference frame and thus remain largely independent products. 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.

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 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.

9. Considerations for Landing Site Selection

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. 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 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 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 (SPA and PSRs).

10. Findings and Recommendations

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The LEAG Advancing Science of the Moon Specific Action Team (ASM-SAT): https://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_185444.pdf

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Objective 5: Observe the Universe from a Unique Location

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Objective 6: Conduct Experimental Science in the Lunar Environment

Lunar Exploration Analysis Group (LEAG) Lunar Exploration Roadmap (LER) (2016, version 1.3) https://www.lpi.usra.edu/leag/roadmap/

NASA Division of Biological and Physical Sciences, https://science.nasa.gov/biological-physical

Objective 7: Investigate and Mitigate Exploration Risks to Humans

Lunar Exploration Analysis Group (LEAG) Lunar Exploration Roadmap (LER) (2016, version 1.3) https://www.lpi.usra.edu/leag/roadmap/

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Cross-Objective Commonality

TBD

Enabling Capabilities

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Considerations for Landing Site Selection

TBD

Findings and Recommendations

TBD

12. Appendix 1: Terms of Reference

Currently available here:
https://www.lpi.usra.edu/announcements/artemis/whitepapers/ToR_Artemis_Science_Definition_Team_FinalSigned.pdf

Will be included in-place in the final report.

13. Appendix 2: Process and Content of the Report

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14. Appendix 3: Biographies of Members

TBD. A list of SDT members follows:

Name	**Affiliation**
Ex-Officio members	
Sarah Noble	HQ
Jake Bleacher	HQ
Debra Needham	HQ
Julie Mitchell/Francis McCubbin	JSC
James Spann	HQ
Kevin Sato	HQ
David Draper	HQ
Chairs	
Renee Weber	MSFC
Sam Lawrence	JSC
Barbara Cohen	GSFC
Civil Servants	
Kelsey Young	GSFC
John Gruener	JSC
Caleb Fassett	MSFC
Noah Petro	GSFC
Jeremy Boyce	JSC
Jennifer Heldmann	ARC
Michael Collier	GSFC
Lisa Gaddis	USGS
Secretary	
Amanda Nahm	HQ/Arctic Slope
Community	
Amy Fagan	Western Carolina U
Juliane Gross	Rutgers U
Carle Pieters	Brown U

15. Appendix 4: List of white papers submitted to the panel

Currently available here: https://www.lpi.usra.edu/announcements/artemis/whitepapers/

Will be included in-place in the final report.

Table 1: Artemis III Science Traceability Matrix

Science Priority is given as High/Medium/Low (we stipulate that "low" doesn't mean a particular investigation is not worth doing, just that it is not regarded as a driving factor). Opportunity enabled by Artemis III is given as Yes/Maybe with modifications (like mobility, specific site, etc.)/Not at this time but maybe in the future.

Artemis Science Objective	Science Goal	Science Investigation	Traceability	Science Priority	Enabled by Artemis III
1. Understanding Planetary Processes	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	L	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	H	Y
		Inventory the variety, age, distribution, and origin of lunar rock types	SCEM 3b	H	M
		Determine the composition, structure, and lateral variability of the crust on global scales.	LER Investigation-Sci-A-5C SCEM 2a, 3c	H	M
		Quantify the local and regional complexity of the current lunar crust	SCEM 3d	M	Y
		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	M	Y
		1b-3. Inventory, relationships, and ages of nonmare rocks.	LER Investigation-Sci-A-5A	H	Y
		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) Also captured in Volcanism and Tectonism	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 Whte paper 2078	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	M	N
	Determine the age of the youngest and oldest mare basalts	SCEM 5b	M	N
	Determine the flux of lunar volcanism and its evolution through space and time	SCEM 5d	L	N
1d. Tectonism: deformation of the crust and thermal history	Determine the stratigraphy of the lunar maria.	LER Investigation-Sci-A-8B	M	N
	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	M	M
		1f-1. Determine physical properties of regolith at diverse locations of expected human activity	SCEM 7b	H	Y
		Understand regolith modification processes (including space weathering), particularly deposition of volatile materials	SCEM 7c	M	Y
		Separate and study rare materials in the lunar regolith	SCEM 7d	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
es	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 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 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

2. Understanding the Character and Origin of Lunar Polar Volatil

	2a-7. Determine distribution of micro cold traps across lunar surface within illuminated regions	SCEM 4a 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	ASM-NC1 LER Investigation-Sci-A-3D LER Investigation-Sci-A-4D	H	Y
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	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	L	Y

	of volatile materials in the near surface.	**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
	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.	Identify the sources of the mid-latitude surface hydroxyl and water	ASM-1, 4b, 4c, 7c, 8d LER Investigation-Sci-A-3D LER Investigation Sci-A-4D	M-H	N
		Determine whether hydrogen products migrate poleward to the cold trap reservoirs	ASM-1, 4b, 4c, 7c, 8d 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	ASM-1, 4b, 4c, 7c, 8d 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**	LER Investigation-Sci-A1 LER Investigation-Sci-A2 LER Investigation-Sci-A3	H	Y
3. Interpreting the Impact History of the Earth-Moon System	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	H	M
		Determine the impact flux during the basin-forming epoch to test the cataclysm hypothesis	SCEM 1a	H	M
	3b. Understand changes to the Earth-Moon bombardment rate	Determine the impact flux throughout the post-basin-forming epoch	SCEM 1c LER Investigation-Sci-B-1B	M	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-L	Y
		Characterize the impact hazard to the Earth-Moon system and present-day impact flux	SCEM 1d	M-L	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. Understand the impact history of the Moon by characterizing the sequence of individual craters and basins that influence local, regional, and global stratigraphy**	LER Investigation Sci-A-8A	H	Y

4. Revealing the Record of the Ancient Sun and Our Astronomical Environment	4a. Understand the history of the Sun, including the composition and flux of the solar wind.	Build a chemical, petrographic, elemental and isotope stratigraphy of volatiles in regolith in a polar cold trap	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-C-2 LER Investigation Sci-B-2	L	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-L	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	L	N
d the Local Space ue Location	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	L	N
		Large Telescope at Earth-Sun L2.	LER Investigation-Sci-C-1D	L	N
		Ultra high-resolution optical imaging of astronomical objects.	LER Investigation-Sci-C-1E	L	N
		Detect gravitational waves.	LER Investigation-Sci-C-1F	L	N
		Large Lunar Optical Telescope.	LER Investigation-Sci-C-1G	L	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	L	N
		5b-1. Near-Lunar Electromagnetic and Plasma Environment.	LER Investigation-Sci-C-2A	H	Y

5. Observing the Universe anc Environment from a Uniq	5b. Heliophysical Investigations using the Moon.	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
		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	L	N
		Detect Changes in the Earth’s Albedo Variability.	LER Investigation-Sci-C-3C	L	N
		Monitor the Earth’s Land/Ocean Surface.	LER Investigation-Sci-C-3D	L	N
		Detect and Examine Infrared Emission of the Earth.	LER Investigation-Sci-C-3E	L	N
		Develop Radar Interferometry of Earth from the Moon.	LER Investigation-Sci-C-3F	L	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
	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
	6c. Investigate interactions of multiphase	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

Conducting Experimental Science in the Lunar Environment	combustion processes and	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	M	N
		Validate relative importance of capillary-driven versus buoyancy-driven flow in various geometries.	LER Investigation-Sci-D-6B	M	N
		Study the behavior of liquid wicking under lunar gravity.	LER Investigation-Sci-D-6C	M	N
	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.	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
		Measure salt deposition rate on heated surfaces in supercritcal water-salt solutions with and without flow.	LER Investigation-Sci-D-8A	L	N

6. (	6h. Investigate precipitation behavior in supercritical water in lunar gravity	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.	LER Investigation-Sci-D-11B	H	M
	7a. Study the fundamental biological and	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

	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, 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 musculo-skeletal 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
		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	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

7. Investigating and Mitigating Exploration Risks	7d. Study the effects of lunar radiation on biological model systems	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
	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
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	M
	Assess metabolic changes affecting bioprocessing potential, virulence, and sensitivity to anti-microbials.	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.	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
7l. Understand lunar	**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

	electrodynamics	**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.**	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	**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.	LER Investigation Sci-D-22B	H	Y