The Lunar Exploration Roadmap:
Exploring the Moon in the 21st Century: Themes, Goals, Objectives, Investigations, and Priorities, 2011

A Community Endeavor Coordinated by the Lunar Exploration Analysis Group (LEAG)

VERSION 1.1 DRAFT

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The Lunar Exploration Roadmap Version 1.1 is the first version of a *living document* that will be updated and further developed over time as more data becomes available from current missions, as further analyses by LEAG Specific Action Teams impact the roadmap, and as other relevant analyses are reported. The Lunar Exploration Roadmap Version 1.1 should **not** be considered as final and suggestions for revisions can be given to the LEAG Chair, the LEAG Executive Secretary or via the e-mail address at the LEAG website (http://www.lpi.usra.edu/leag).

The three themes described below and in the companion Excel spreadsheet, are at various degrees of fidelity. The Science Theme has a long heritage of study, including NRC studies, and represents community consensus. The Feed Forward Theme has been presented to the Mars Exploration Program Analysis Group and their comments have been incorporated. This theme is now expanded to include using the Moon to go to other airless bodies. The Sustainability Theme is at the lowest fidelity, representing a small (but growing) body of opinion, and will require refinements, which have begun at the LEAG Annual Meetings.

Overall the roadmap is intended to layout an *integrated* and *sustainable plan* for lunar exploration that will allow NASA to transition from the Moon to Mars (and beyond) without abandoning the lunar assets built up using tax payer dollars. As such, the roadmap will enable commercial development, through early identification of "commercial on ramps", that will create wealth and jobs to offset the initial investment of the taxpayer. In addition, the roadmap will, with careful planning, enable international cooperation to expand our scientific and economic spheres of influence while enabling an expansion of human *and* robotic space exploration.

The Lunar Exploration Roadmap builds upon previous work over the last several decades that has been devoted to lunar exploration. It does not represent a reinvention of past efforts to return to the Moon, but rather it incorporates these efforts into an integrated plan for sustained plan for lunar exploration. The roadmap has traceability back to such documents as:

- The Report from the Lunar Geoscience Observer Workshop (1986);
- The Status and Future of Lunar Geoscience (1986);
- 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 (LExSWG, 1992);
- Lunar Surface Exploration Strategy (LExSWG, 1995);
- New Frontiers in the Solar System: An Integrated Exploration Strategy (2003) (Decadal Survey);
- A Renewed Spirit of Discovery: The President's Vision for US Space Exploration (2004);
- 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 (2006);
- 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.

The Lunar Exploration Roadmap is a hierarchical document that is comprised of three themes with subsequent goals, objectives, and investigations or initiatives (where appropriate). The three themes address the question "Why are we going back to the Moon?" and focus on Science, Feed Forward (to Mars and beyond) capabilities, and Sustainability (see below).

There are a number of cross cutting themes that permeate throughout all three main themes:

- Learn to live and work successfully on another world.
- Expand Earth's economic sphere to encompass the Moon, and pursue lunar activities with direct benefits to life on Earth.
- Strengthen existing and create new global partnerships.
- Engage, inspire, and educate the public.

This document is arranged by theme where the goals, objectives and investigations are outlined for each theme. The objectives and investigations are, where possible, prioritized and time phased. Next, the time phasings and prioritizations are used to create the roadmap (in the companion Excel spreadsheet).

Time Phasing Criteria

In many cases, Investigations and Objectives have been time phased using Early Stage, Middle Stage, and Late Stage. Definitions of these terms are:

EARLY: Robotic precursors and up to the second human landing (≤1 lunar day).
MIDDLE: Initial outpost build-up to including stays of 1 lunar day and including part of the lunar night, as well as Robotic missions.
LATE: Outpost established, stays of >30 days, including Robotic missions.

In the discussion of the various Themes, time phasing and prioritization of the Objectives and Investigations are given. If the Investigations under a given Objective have variable prioritizations and time phasings, these will be given for each Investigation. Investigation prioritization and time phasing will not be given if they are all the same as those for the Objective.

For roadmapping efforts, the Early Stage has been subdivided into pre-Early (Robotic Precursor Missions) and Early (Robotic & Short Human Sortie ≤1 Lunar Day).

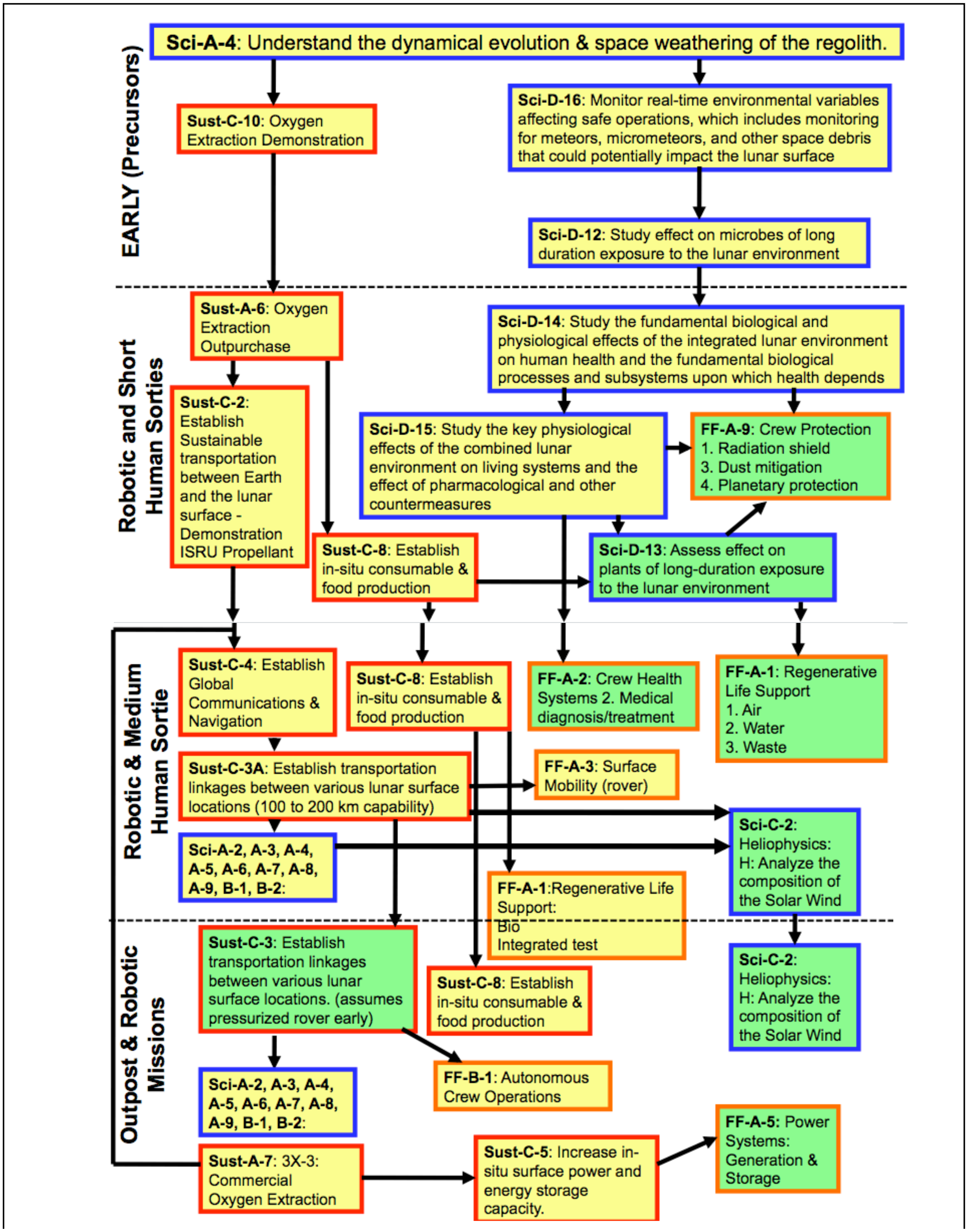
Prioritization Criteria

Low, medium, and high prioritizations have been assigned by the LEAG roadmapping team to the Objectives and Investigations in terms of what we have interpreted, through contact with leaders in the community, as general thinking of how particular science communities (i.e., Earth Observing, Heliophysics, and Astrophysics) could best use the Moon. For lunar science, we defer to the NRC (2007) Scientific Context for the Exploration of the Moon report for prioritization of science concepts and goals, which specifically studied the issue of prioritization. The priorities are intended to help gauge, within the range of uses of the Moon that have been proposed over the years within these communities, which concepts appear to offer the most promise.

Low Priority: Would be good to do, but is not essential for habitat/exploration development;
Would only give an incremental advance to our scientific knowledge;
and/or Could be conducted more efficiently elsewhere.
Medium Priority: Falls in between Low and High Priority. Could be enabled with sufficient infrastructure investment.

High Priority: Is essential to do in order to make progress in habitat/exploration development;
Would facilitate a fundamental advance in our scientific knowledge;
Is facilitated by or should be facilitated by the Lunar Architecture;
and/or Is best done on the lunar surface.

Given these criteria, an integrated roadmap is being developed that maps between themes and shows how objectives/investigations in one theme impact those in another. As an example of this, Objective Sci-A-4 (Understand the dynamical evolution and space weathering of the regolith), a high priority objective, is taken as a starting point (Figure 1):



A summary of the Themes, Goals, and Objectives within the roadmap are given below:

SCIENCE (Sci) THEME: Pursue scientific activities to address fundamental questions about the solar system, the universe, and our place in them.

GOAL Sci-A: Understand the formation, evolution, and current state of the Moon:

- **Objective Sci-A-1**: Understand the environmental impacts of lunar exploration (2 Investigations);
- **Objective Sci-A-2**: Development and implementation of sample return technologies and protocols (4 Investigations);
- **Objective Sci-A-3**: Characterize the environment and processes in lunar polar regions and in the lunar exosphere (4 Investigations);
- **Objective Sci-A-4**: Understand the dynamical evolution and space weathering of the regolith (5 Investigations);
- **Objective Sci-A-5**: Understand lunar differentiation (5 Investigations);
- **Objective Sci-A-6**: Understand volcanic processes (4 Investigations);
- **Objective Sci-A-7**: Understand the impact process (5 Investigations);
- **Objective Sci-A-8**: Determine the stratigraphy, structure, and geological history of the Moon (4 Investigations);
- **Objective Sci-A-9**: Understand formation of the Earth-Moon system (3 Investigations).

GOAL Sci-B: Use the Moon as a "witness plate" for solar system evolution:

- **Objective Sci-B-1**: Understand the impact history of the inner Solar System as recorded on the Moon (4 Investigations);
- **Objective Sci-B-2**: Regolith as a recorder of extra-lunar processes (5 Investigations).

GOAL Sci-C: Use the Moon as a platform for Astrophysical, Heliophysical, and Earth-Observing studies;

- **Objective Sci-C-1**: Astrophysical and Basic Physics Investigations using the Moon (8 Investigations);
- **Objective Sci-C-2**: Heliophysical Investigations using the Moon (12 Investigations);
- **Objective Sci-C-3**: Use the Moon as a platform for Earth-observing studies (8 Investigations).

GOAL Sci-D: Use the unique lunar environment as research tool.

- **Objective Sci-D-1**: Investigate and characterize the fundamental interactions of combustion and buoyant convection in lunar gravity (4 Investigations);
- **Objective Sci-D-2**: Perform tests to understand and possibly discover new regimes of combustion (3 Investigations);
- **Objective Sci-D-3**: Investigate interactions of multiphase combustion processes and convection at lunar gravity (3 Investigations);
- **Objective Sci-D-4**: Use the unique environment of the lunar surface to perform experiments in the area of fundamental physics (4 Investigations);
- **Objective Sci-D-5**: Obtain experimental data to anchor multiphase flow models in partial gravity environment (3 Investigations);
- **Objective Sci-D-6**: Study interfacial flow with and without temperature variation to anchor theoretical/numerical models (3 Investigations);
- **Objective Sci-D-7**: Study behavior of granular media in the lunar environment (2 Investigations);
- **Objective Sci-D-8**: Investigate precipitation behavior in supercritical water in partial gravity environment (2 Investigations);
- **Objective Sci-D-9**: Investigate the production of oxygen from lunar regolith in lunar gravity (2 Investigations);
- **Objective Sci-D-10**: Investigate the behavior of liquid-phase sintering under lunar gravity (1 Investigation);
- **Objective Sci-D-11**: Study and assess effects on materials of long-duration exposure to the lunar environment (2 Investigations);
- **Objective Sci-D-12**: Study effect on microbes of long-duration exposure to the lunar environment (3 Investigations);
- **Objective Sci-D-13**: Assess effect on plants of long-duration exposure to the lunar environment (2 Investigations);
- **Objective Sci-D-14**: 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 depends (2 Investigations);
- **Objective Sci-D-15**: Study the key physiological effects of the combined lunar environment on living systems and the effect of pharmacological and other countermeasures (3 Investigations);
- **Objective Sci-D-16**: Evaluate consequences of long-duration exposure to lunar gravity on the human musculo-skeletal system (3 Investigations);

Objective Sci-D-17: Study the effects of lunar radiation on biological model systems (5 Investigations);

Objective Sci-D-18: 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 (4 Investigations);

Objective Sci-D-19: 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;

Objective Sci-D-20: 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 (1 Investigation);

Objective Sci-D-21: Understand the impact of Lunar environments on terrestrial life forms and multiple generations of life that impact human health (2 Investigations);

Objective Sci-D-22: 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 (2 Investigations).

FEED FORWARD (FF) THEME: Use the Moon to prepare for future missions to Mars and other destinations.

<u>GOAL FF-A</u>: Identify and test technologies on the Moon to enable robotic and human solar system science and exploration:

Objective FF-A-1: Develop surface life support systems to reduce risks associated with long duration Martian surface stay times (7 Investigations);

Objective FF-A-2: Develop Crew Health Systems That Enable Safe, Long Duration, Surface Stays (4 Investigations);

Objective FF-A-3: Develop surface mobility capabilities that allow human crews to efficiently and safely explore the surface of Mars (3 Investigations);

Objective FF-A-4: Develop the capability to acquire and use local resources to sustain long-term exploration and habitation of planetary surfaces (6 Investigations);

Objective FF-A-5: Develop the capability to produce adequate levels of power on planetary surfaces to allow human crews to work and live productively (3 Investigations);

Objective FF-A-6: Develop the capability to autonomously land safely and accurately on Mars (3 Investigations);

Objective FF-A-7: Develop the capability to provide or construct structures on planetary surfaces adequate for long-duration habitation by humans, and made of materials that will endure extended exposure to the deep-space environment (2 Investigations);

Objective FF-A-8: Develop the capability for crews on Mars to communicate with other assets on the surface, and navigate to and from those assets (5 Investigations);

Objective FF-A-9: Develop the capability for human crews to operate safely on planetary surfaces, protected from the extreme environment and hazards (5 Investigations).

<u>GOAL FF-B</u>: Use the Moon as a test-bed for missions operations and exploration techniques to reduce the risks and increase the productivity of future missions to Mars and beyond:

Objective FF-B-1: Develop the capability for autonomous crew operations on the Moon and Mars (5 Investigations);

Objective FF-B-2: Develop the capability for productive and efficient human-robotic interaction in the exploration of planetary surfaces (4 Investigations);

Objective FF-B-3: Establish an administrative structure and cost effective surface systems to facilitate strong international cooperation (4 Investigations).

<u>GOAL FF-C</u>: Preparing for future missions to other airless bodies:

Objective FF-C-1: Ability to operate on a geologic surface (3 Investigations);

Objective FF-C-2: Develop the capability for autonomous crew operations (Corollary to Feed-Forward Objective FF-A-6) (6 Investigations);

Objective FF-C-3: Development and implementation of sample return technologies and protocols (Corollary to Feed-Forward Objective Sci-A-2) (4 Investigations).

Objective FF-C-4: Understand planetary differentiation (Corollary to Feed-Forward Objective Sci-A-5) (1 Investigation);

Objective FF-C-5: Regolith as a recorder of Solar-System processes (Corollary to Feed-Forward Objectives Sci-A-4 & Sci-B-2) (3 Investigations);
Objective FF-C-6: Develop the capability for human crews to operate safely on planetary surfaces, protected from the extreme environment and hazards (Corollary to Feed-Forward Objectives Sci-D-11, Sci-D-14, Sci-D-18) (4 Investigations).
Objective FF-C-7: Develop the capability for productive and efficient human-robotic interaction in the exploration of planetary surfaces (Corollary to Feed-Forward Objective FF-B-2) (6 Investigations);
Objective FF-C-8: Develop Crew Health Systems that enable safe, long duration, missions (Corollary to Feed-Forward Objective FF-A-2) (3 Investigations);
Objective FF-C-9: Establish an administrative structure and cost effective surface systems to facilitate strong international cooperation (Corollary of Feed-Forward Objective FF-B-3) (4 Investigations).
Objective FF-C-10: Develop the capability to acquire and use local resources to sustain long-term exploration crews (Corollary of Feed-Forward Objective FF-A-4) (3 Investigations);
Objective FF-C-11: Establishment of in-situ resource utilization systems (Corollary to Feed-Forward Objectives Sust-A-3, Sust-B-9) (7 Investigations);

SUSTAINABILITY (Sust) THEME: Extend sustained human presence to the Moon to enable eventual settlement.

<u>GOAL Sust-A</u>: Maximize Commercial Activity:

Objective Sust-A-1: Establish policies and implementation of comprehensive, coordinated governmental and intergovernmental action to foster space commerce (3 Initiatives);
Objective Sust-A-2: Preparation for Commerce I: Conduct a comprehensive resource and market assessment of commercial support for scientific and exploration activities on the Moon (3 Initiatives);
Objective Sust-A-3: Preparation for Commerce II: Conduct small-scale demonstrations of potentially commercial lunar support services for scientific and exploration activities on the Moon (2 Initiatives);
Objective Sust-A-4: Transition to Commerce I: Conduct pilot-plant scale demonstrations of potentially commercial lunar support services for scientific and exploration activities on the Moon (6 Initiatives);
Objective Sust-A-5: Transition to Commerce II: Commercially provided lunar support services for scientific and exploration activities on the Moon (5 Initiatives);

<u>GOAL Sust-B</u>: Enable and Support the Collaborative Expansion of Science and Exploration:

Objective Sust-B-1: Implementation of comprehensive, coordinated integration of diverse scientific and exploration activities to maximize complementary operations and minimize operational and environmental conflicts (5 Investigations);
Objective Sust-B-2: Establishment and implementation of comprehensive site-selection criteria and processes (2 Investigations);
Objective Sust-B-3: Development of surface power and energy storage systems (9 Investigations);
Objective Sust-B-4: Establishment of sustainable transportation between Earth and the lunar surface (6 Investigations);
Objective Sust-B-5: Deployment of Robotic Facilities for Science and Exploration Operations (12 Investigations);
Objective Sust-B-6: Establishment of Global Communications and Navigation Capability (5 Investigations);
Objective Sust-B-7: Establishment of sustainable human transportation between lunar sites (4 Investigations);
Objective Sust-B-8: Deployment of habitat and laboratory facilities for human science and exploration operations (9 Investigations);
Objective Sust-B-9: Establishment of in-situ production of life-support, power system reagents, propellants and related resources (10 Investigations);
Objective Sust-B-10: Establishment of in-situ food production capability (2 Investigations);
Objective Sust-B-11: Establishment of in-situ repair, fabrication, manufacturing and assembly capability (8 Investigations);
Objective Sust-B-12: Establishment of integrated design, development and testing capability (5 Investigations).

<u>GOAL Sust-C</u>: Enhance Security, Peace and Safety:

Objective Sust-C-1: Detection and mitigation of threats from Near-Earth objects (2 Initiatives);
Objective Sust-C-2: Beamed power and other lunar-based energy sources for terrestrial consumption (commercial on ramp) (2 Initiatives);
Objective Sust-C-3: Remote and Hazardous Research and Testing (e.g., bio/nano technology) (2 Initiatives);

Objective Sust-C-4: Applied Earth observations (1 Initiative);
Objective Sust-C-5: Archiving of Critical Human Records and Biological Samples (2 Initiatives).

<u>Science (Sci) Theme</u>: Pursue scientific activities to address fundamental questions about the solar system, the universe, and our place in them.

<u>Goal Sci-A</u>: Understand the formation, evolution, and current state of the Moon.

The Moon has been and will continue to be the scientific foundation for our knowledge of the early evolution and impact history of the terrestrial planets. Remotely sensed, geophysical, and sample data allow us to define investigations that test and refine models established for lunar origin and evolution. For example, documenting the diversity of crustal rock types and the composition of shallow and deep lunar mantle will allow refinement of the lunar magma ocean hypothesis. Dating the formation of large impact basins will relate directly to the crustal evolution of all the terrestrial planets and, possibly, to the bombardment history of the outer Solar System. The rationale for studying the Moon and a list of major problems to address has been presented in many previous reports, most recently by the NASA Advisory Council's 2007 *Workshop on Science Associated with the Lunar Exploration Architecture* and the National Research Council's *The Scientific Context for Exploration of the* Moon (National Academies Press, 2007).

A note about time phasing of science investigations: Time phasing of objectives Sci-A-1 through Sci-A-3 is driven by human environmental impact, architectural considerations, and operational protocols and do not reflect a prioritization based on science. All other science objectives can and should be done during all time phases—they are ***not*** prioritized because all are pursued simultaneously during all phases of lunar exploration. All require similar exploratory infrastructure (tools, equipment, procedures, etc.).

<u>Objective Sci-A-1</u>: Understand the environmental impacts of lunar exploration.

ISRU (In-Situ Resource Utilization) operations and extensive settlement will affect the environment of the Moon, creating a new field of lunar environmental science. Tracking environmental changes associated with human activity will entail installation of sensors at varying distances from an outpost or settlement. Lunar exploration provides an important opportunity to monitor the effects of human presence on biological and organic contamination, and to develop ways to mitigate them. This activity will help prepare for human missions to Mars by developing methods to test and minimize contamination and to understand the nature of such contamination.

Time Phasing:
<u>Early</u>: Earth-based observations, orbital observations (e.g., LRO, LADEE), soft lander with, for example, volatile sensor/mass spectrometer.
<u>Middle</u>: Early human missions deploy sensor network, volatile release experiment.
<u>Late</u>: Monitor, expand the network.

Science Priority: Medium

Rationale: Extensive activity will change the lunar environment, so we need to understand the natural state as early as possible. Will help to develop methods to test and minimize contamination of Mars by human missions.

Investigation-A: Characterize the lunar exosphere and current gas/surface interactions to determine baseline lunar environment

Characterize the composition and spatial and temporal variability of the natural lunar exosphere including electrostatically lofted dust prior to large-scale human presence on the Moon. Conduct controlled volatile-release experiments to understand surface transport of volatile atoms and molecules in the lunar environment, including movement to polar cold traps under varying magnetospheric conditions. It may also be useful to do a controlled dust experiment. Understand original lunar "atmosphere" before it is irrevocably changed. Characterize transport of volatile elements on the lunar surface as a guide toward understanding the genesis and chemical processing of polar volatile deposits on airless planets. Note that this investigation requires modern instruments to measure exospheric composition *in* situ, and that such instruments need to be developed. Meteoroid bombardment, solar flare events, and large moonquakes are all potential hazards for occupants at a lunar outpost or permanent settlement. It is important to determine before human habitation the environmental effects of such events, to help in designing systems to mitigate their effects.

Time Phasing:
Early: This needs to be done early prior to human return and can be conducted using Earth-based observations, orbital observations (e.g., LRO, LADEE), soft lander.

Science Priority: Medium (establishes a baseline for the lunar environment)

Rationale: See the Objective Rationale.

Investigation-B: Determine how the environment changes after the return of humans to the Moon.

Monitoring environmental changes associated with human activity will entail installation of sensors at varying distances from an outpost or settlement, beginning before human arrival and continuing afterwards. Measurements need to include volatiles and organic compounds and how their concentrations vary with distance from a lunar outpost and the extent to which they react with lunar materials and migrate into the regolith. Instruments used for this characterization must have gone through appropriate contamination control so we know what was brought along or developed on the surface in order to identify and quantify what is currently on the surface. Any material released on the surface or in the atmosphere should not occur in nature and should provide a unique signature to ensure that their source in future missions is known.

Time Phasing:
Middle & Late: Monitor the lunar environment as landings increase and human presence becomes more long term.

Science Priority: Medium (as a follow on to Investigation A). Early human missions deploy sensor network, volatile release experiment followed by monitoring and expanding the network of sensors.

Rationale: See the Objective Rationale.

<u>Objective Sci-A-2</u>: Development and implementation of sample return technologies and protocols.

The geological exploration of the Moon or any other planetary body will involve field observations and measurements, deployment of geophysical equipment, and sample collection. Sampling involves understanding how to collect samples, documenting their geologic context, lunar surface curation of the samples, outpost laboratory characterization, and protocols for their transport to Earth. Samples will be collected for geological, materials science, and biological studies. Acquisition, storage, return, and curation of samples requires the development of protocols and technologies that allows selection of appropriate materials and protects their integrity.

Investigations A-D are all relevant to the sampling of any planetary body.

Time Phasing (applies to all Investigations):
<u>Early</u>: All investigations need to be started early.
<u>Middle</u>: Modify techniques as experience with *in situ* sample analysis improves and infrastructure develops.
<u>Late</u>: Continue to modify techniques as experience with *in situ* sample analysis improves and infrastructure develops.

Science Priority (applies to all Investigations): High (enables high priority science).

Rationale: This activity can influence mass, volume, and structural issues associated with Altair lander and crew rovers.

<u>Investigation-A</u>: Develop a sampling strategy

Geologic investigations will be a prime scientific function of crews on the lunar surface. This includes extensive field observations that guide sample selection. It is important to have a guiding strategy for the interplay of field observations by humans and by robotic devices with sample collection and documentation. It is critical to understand the geological style of the Moon, including the nature of impact mixing at all scales, the contribution of distant events to site geology, and nature of complex, polygenetic regional units. Determine which sample targets on the Moon are appropriate for reconnaissance sampling versus detailed field study (see Ryder, Spudis, and Taylor, 1989).

<u>Investigation-B</u>: Understand the scientific requirements for sample curation, packaging, and transport to Earth.

Provide the capability to curate samples on the Moon before transporting them to Earth. Such curation involves protecting samples from contamination while on the Moon and during preparation for shipping and transport to Earth. It also requires development of an information system to document samples (collection locality, specimen type, location in curatorial facility, etc.). It applies to biological and engineering, as well as geological samples, and to samples relevant for resource extraction experiments. To make accurate analyses of geological samples collected on the Moon, the samples must be kept clean from contamination by other samples and habitat gases, dust, and other human-generated materials. A large number of samples will be collected, so it is also important to keep track of each one and its collection location to avoid confusion during later analysis. For successful planning, we must determine what analyses will be made on geological, materials science, and biological materials to establish appropriate controls on contamination.

Investigation-C: Understand what analyses (field and laboratory) need to be done *in situ* to aid field studies and optimize the value of samples returned to Earth.

Develop reliable and largely automated analytical instruments for use on the surface to screen samples to choose which to return to Earth. Analytical instruments at a lunar base (or Mars) will allow us to optimize the samples to be returned to Earth, making the best use of cargo space and mass. It also allows the crew to use preliminary data on samples to help plan additional field observations. A high degree of automation is required so that astronauts do not have to spend significant amounts of time analyzing rocks and soils. However, it is crucial to determine the optimal types of analyses and instruments needed.

Investigation-D: Enhance curatorial facilities on Earth to handle environmentally-sensitive samples (e.g., ices)

It may be necessary to transport environmentally-sensitive samples to Earth for detailed analysis. Examples include volatiles and ices from permanently-shadowed regions at the poles and regolith samples for studies of loosely-bound solar wind products. Thus, sample packaging and transport methods and equipment need to be designed and implemented. Once received on Earth, they must be curated under appropriate conditions.

Objective Sci-A-3: Characterize the environment and processes in lunar polar regions and in the lunar exosphere.

The Moon's spin axis is nearly normal to the ecliptic (88.5° inclination), resulting in locations of permanent darkness and quasi-permanent sunlight near the poles. The dark regions are extremely cold and if any volatile material gets into them, they cannot escape, becoming "trapped" for geological time spans. The possibility of trapped volatiles in the lunar polar regions is important for both scientific and operational reasons. They record the history of the influx of volatile components on the Moon for at least the last two billion years, possibly yielding clues to source regions and their evolution with time. Lunar polar volatiles are also important as a resource to support human habitation and exploration of the Moon and the industrialization of cislunar space.

Time Phasing:
Early: Orbital mapping and characterization of cold traps, sunlight, polar deposits. Surface characterization from lander.
Middle: Bedrock geology during early human missions.

Late: Active volatile release experiment and network.

Science Priority: High

Rationale: See individual Investigations.

Investigation-A: Map and characterize polar cold traps

Determine the extent, settings, physical properties and locations of permanently dark cold traps near the lunar poles. Understand the thermal environment of these areas, including the effects of this thermal regime on lunar regolith and geotechnical properties. Understand the temporal history of lunar cold traps.

Time Phasing:
Early: Orbital mapping and characterization of cold traps, sunlight, polar deposits. Surface characterization from lander.

Science Priority: High

Rationale: It is likely that new and unexpected science will result from study of this unique environment. We need to understand early the nature of polar volatiles and the environment to make ISRU architectural decisions.

Investigation-B: Map and characterize quasi-permanently illuminated areas

Determine the extent and location of permanent and quasi-permanently sunlit areas near the poles, with particular emphasis on their physical and morphological properties with an eye towards their use as sites for a lunar outpost. Map the time history of any eclipse periods in these areas. Understand the thermal and electrical environment of these areas, including the charging history and any dust phenomenology induced by it.

Time Phasing:
Early: Orbital mapping and characterization of cold traps, sunlight, polar deposits. Surface characterization from lander.

Science Priority: High

Rationale: Characterizing all aspects of the lunar poles is critical in determining if the North/South Pole should be the site of the lunar outpost.

Investigation-C: Determine bedrock geology of polar regions

Understand the geological setting of both polar areas, including their relation to local and distant impact craters and basins and regional compositional provinces. Map and determine the structure of local geological features and their relation to polar volatile deposits and micro-environments.

Time Phasing:

Middle-Late: This Investigation will build upon the Early ones and will require more infrastructure in order to undertake more detailed studies of the polar regions.

Science Priority: High

Rationale: It is likely that new and unexpected science will result from study of this unique environment.

Investigation-D: Understand volatile sources and mechanisms of transport and deposition

Characterize the volatile phase in the permanently shadowed regions near the lunar poles, and determine their concentrations, chemistry, mineralogy, phase relations, temperatures, and geotechnical properties. It is important to characterize volatiles possibly present in lunar polar regions because they may be of considerable value to the lunar exploration program, and because they may reveal the chemical nature of impactors on the Moon through time. This investigation has significant value to Lunar Resource Utilization. It requires measurement of the concentrations of volatile species from the solar wind, the regolith, volcanic deposits, present-day degassing of the lunar interior, and exogenic sources such as comets.

Time Phasing:
Middle-Late: This Investigation will build upon the Early ones and will require more infrastructure in order to undertake more detailed studies of the polar regions. This will require landers to undertake detailed examinations of the permanently shadowed regions.

Science Priority: High

Rationale: This Investigation also builds upon the earlier ones and requires detailed analyses of the deposits in the permanently shadowed regions.

Objective Sci-A-4: Understand the dynamical evolution and space weathering of the regolith.

Impacts produce a surface regolith on all planetary objects without atmospheres. Because such regoliths are an important part of local surface geology on such bodies, it is important to study the processes and end products associated with them.

Time Phasing:
Early: Orbital remote sensing, surface lander characterization (inc. geotechnical).
Middle: Comprehensive sampling around lander (100's m) to depths up to 3 m (e.g., trenching, drilling, crater walls), geotechnical, ability to sample steep slopes, geophysical profiling, robotic sampling of remote sites.
Late: Comprehensive sampling to greater ranges (km) to depths up to 10's of m (e.g., trenching, drilling, crater walls), regolith/bedrock interface, extensive and intensive sampling, paleoregolith identification and sampling, ability to sample steep slopes, geophysical profiling, robotic sampling of remote sites.

NOTE: Overall timing applies to all, except Investigation D, which is **Middle-Late**.

Science Priority: High

Rationale: This objective helps us to understand lunar processes and history; Investigations 1 and 5 affect surface operations such as trafficability.

Investigation-A: Characterize the structure and layering of the regolith, including the interface with underlying bedrock

Determine lunar regolith properties, such as structure (layering and depth variations), composition, and properties of dust, and modes of formation and evolution of the regolith. Understand the extent of vertical and lateral mixing of materials. Determine the temporal history of regolith components, including the production and nature of "paleoregolith."
Time phasing: Detailed study of in place regolith is an important priority at a lunar outpost site; this can be done by large-scale digging (10's of meters) of a section of regolith, including trenching and pit excavation. Drilling through the regolith, which might be done for resource exploration, will also be useful. Detailed studies require the existence of a permanently-occupied lunar facility, hence late in the program.

Investigation-B: Determine the compositional variability of the regolith and how it relates to underlying rock

An important part of understanding the composition of the crust and how the regolith is produced is to determine the details of how it relates to the underlying rock. This includes the extent of mixing from different depths and from more distant sources. Assess the efficacy of lateral and vertical mixing of materials.

Investigation-C: Characterize the lunar regolith to understand space weathering processes in different crustal environments

Characterize the space weathering process for the exposed lunar surfaces at various ages, which is caused by micrometeorite impacts, solar-wind implantation, and solar irradiation. The lunar regolith bears witness to the process of space weathering, the interactions between the surface and space. Such interactions can be extrapolated to other airless bodies such as Mercury. These interactions preserve a record of solar activity and evolution. Because impacts produce a variety of surface ages on the lunar surface, from very new to ancient, the Moon is the best available laboratory to study the space weathering that has occurred on all of the airless bodies in the solar system.

Investigation-D: Characterize volatile concentrations and transport mechanisms

The dynamic surface environment may lead to redistribution of solar-wind and other volatiles within the regolith. Little is known quantitatively about the extent of mobilization and the transport mechanisms, so detailed measurements of the volatile abundances are needed. The current lack of quantitative understanding limits our ability to extract the past record of the Sun or of volatile release from the lunar interior. In particular, we don not fully understand the nature and efficacy of the retention mechanisms for solar wind gas in soils of varying types; this topic is critical to assessing techniques of in situ resource utilization. Migration of volatiles in the lunar regolith also bears on the transport of volatiles through the exosphere as the regolith may be an important source of volatiles.

Investigation E: Determine the geotechnical properties of the lunar regolith.

The geotechnical properties are important for understanding the formation of the regolith and for designing construction and excavation techniques. Pertinent properties include grain size distribution, particle shapes, density, bearing capacity, cohesion, shear strength, and thermal conductivity (all as a function of depth), and slope stability and trafficability (the capacity of a soil to support a vehicle and to provide sufficient traction for movement).

Objective Sci-A-5: Understand lunar differentiation.

The Moon is a small, differentiated planet; study of its crust will allow us to better understand early planetary evolution and crustal genesis. The Moon presents the best opportunity to geochemically characterize early fundamental processes in a planetary body of substantial size, including the differentiation into component parts, the production of a crust, and the genesis of basalts from various depths in the mantle. It also allows us to study the processes involved in its earliest differentiation (probably involving a globe-encircling magma ocean) and the transition to subsequent magma production by a series of magmatic events probably driven by convection in the mantle.

Time phasing (applies to all Investigations):

Early: Remote sensing of rock types, robotic sample return, global network, surface rovers (Lunakhod).

Middle: Search for and sampling of bedrock, comprehensive sampling near lander, field relations of bedrock geology, emplace network stations, geophysical profiling of lunar interior, robotic sampling of remote sites.

Late: Search for and sampling of bedrock, extend range of field mapping and sampling, regional geophysical network, robotic sampling of remote sites.

Science Priority: High

Rationale: Understand lunar processes and geological history.

<u>Investigation-A</u>: Inventory, relationships, and ages of nonmare rocks

Rocks in the lunar crust shed light on the processes that operated in the lunar magma ocean, the range of magma compositions subsequent to primary differentiation, and the chemical and mineralogical composition of their mantle source regions. This investigation involves synthesizing remote sensing and sample data to inventory and map rock types, determine their sequence and structure within the crust, and reconstruct crustal evolution in space and time. Using remote sensing as a guide, it is necessary to sample the crust broadly to determine lateral or regional variations, using ejecta from craters and basins to access varying depth levels. Precise age determinations require returning samples for analysis in terrestrial laboratories.

<u>Investigation-B</u>: Inventory, relationships, and ages of mare volcanics and related intrusive rocks

Mare volcanic deposits contain information about the composition and thermal history of the lunar mantle and hence, its bulk composition. Map the sequence, thicknesses, and ages of volcanic units in the maria. Establish the spatial and temporal variations in mare basalt composition. Map the extent and composition of ancient (pre-3.9 Ga) mare volcanism and determine its possible relation to the last of the basin-forming impacts or to the insulation characteristics of the megaregolith. Map the extent and composition of lunar pyroclastic deposits, including their associated crystalline components. Understand the physical processes involved in the generation, ascent, eruption, and emplacement of mare magmas and deposits and how they change with time.

<u>Investigation-C</u>: Determine the composition, structure, and variability of the crust

This investigation involves detailed study of the variability of the thickness and composition of the lunar crust, both vertically and laterally. It requires a synthesis of remote sensing, geophysical measurements, sample analysis, and in the long term, drilling to depths of a few hundred meters.

<u>Investigation-D</u>: Determine the composition, structure, and variability of the mantle

Determining the composition of the mantle is essential for determining the bulk composition of the Moon, which is a major piece of information for understanding the physical and chemical environment during the formation of the Earth-Moon system. Knowledge of the composition of the lunar mantle, as inferred from its melt products, and the lateral and vertical variations that exist, can be used to place important constraints on the Moon’s thermal and internal evolution. Central topics include core-mantle-crust transitions, differences between the lower and upper mantle (if any), phase heterogeneity, degree of seismic activity, the foci for Moonquakes, lower crust/upper mantle interactions, planetary anisotropy, and seismic hazards for future experiments and structures.

<u>Investigation-E</u>: Determine size and composition of the core

Unequivocally establishing the presence or absence of a lunar core, its physical state (e.g., solid or liquid, with or without a silicate component), its size and chemical composition and density, and establishing the nature of the deep lower mantle will aid in estimating the bulk composition of the Moon and global differentiation processes. It will also help to understand the lunar magnetic record. This investigation involves geophysical measurements of the deep lunar interior and sample analyses of the paleomagnetic properties of lunar rocks. Rock measurements should focus on oriented samples, although still provide important information about the intensity of the magnetic field, hence test the possibility of a core dynamo.

Objective Sci-A-6: Understand volcanic processes.

The physical volcanology of the Moon includes study of mare basalt lavas and pyroclastic eruptions. This work sheds light on lava flow emplacement mechanisms, eruption fluxes, the rate of magma production in the mantle and their variation through time, magma migration mechanisms, and the thermal history of the mantle. A particularly important area to study is the nature and source of volatiles associated with volcanic eruptions of both lava flows and pyroclastic deposits. The concentration of volatiles in the Moon has great bearing on testing ideas for planetary accretion and lunar origin.

Time phasing (applies to all Investigations):

Early: Remote sensing of rock types, robotic sample return, geomorphology of volcanic landforms, surface rovers (EGA/MS).

Middle: Search for and sampling of oriented bedrock, volcanic stratigraphy, comprehensive sampling near lander, field relations of bedrock geology, emplace network stations, geophysical profiling of lunar interior, robotic sampling of remote sites.

Late: Search for and sampling of bedrock, extend range of field mapping and sampling, regional geophysical network, robotic sampling of remote sites.

Science Priority: High

Rationale: Understand lunar processes and geological history.

Investigation-A: Determine how magma is generated and transported to the surface

Understand the physical processes involved in the generation, ascent, eruption and emplacement of mare magmas and deposits and how these processes change with time. Understand the variety, geometry, locations, and processes associated with volcanic vents, including magma devolatilization and the possibility of mantle xenoliths.

Investigation-B: Determine how lava flows are emplaced on the Moon

This investigation involves mapping the sequence, thickness, and age of volcanic units in the maria, establishing the spatial and temporal variations in mare basalt composition, and mapping the extent and composition of lunar pyroclastic deposits. We must develop criteria to distinguish between fissure-fed, flood lava eruptions and low effusion, central vent volcanism. It also includes mapping the extent and composition of ancient (pre-3.9 Ga) mare volcanism and determine possible relations with the last of the basin-forming impacts.

Investigation-C: Determine the physical characteristics of pyroclastic deposits and vents

Pyroclastic volcanism has produced local and regional dark mantle deposits, comprising particles of negligible to significant crystallinity. Such eruptions are thought to be driven by $CO+CO_2 \pm SO_2$, which either produce energetic fountains of rapidly-quenched glassy droplets or become trapped in the near surface to produce discrete explosions dominated by disaggregated crystalline cap rock. This investigation aims to place constraints on pyroclastic deposit thicknesses, particle size distributions, and cooling histories, all of which will allow us in principle to constrain the locations of source vents. One issue that needs to be resolved is whether a deposit is the result of a single protracted eruption at a single site or multiple eruptions from distributed sources.

Investigation-D: Assessment of the volatiles driving lunar volcanic eruptions

Determine the origin of endogenous lunar volatiles (e.g., degassing of the mantle) and the redistribution of these volatiles by geologic processes operating over time. Knowledge of the origin and distribution processes of volatiles will lead to predictive models of their distribution on a broad scale. Although the Moon is a volatile-poor body, characterizing the uncommon occurrence of its more readily volatilized elements can address questions of lunar origin and the chemical nature of its interior. Of special significance for investigation are the volcanic glass deposits because in some cases these represent deep and relatively unfractionated mantle materials. This task includes study of reported modern gas emissions from the Moon and includes typical volcanic gases (H_2O, CO, CO_2 and SO_2), as well as other gases that may serve as tracers of gas release (e.g., ^{222}Rn, ^{40}Ar).

Objective Sci-A-7: Understand the impact process.

Study and understand the various phases of the impact process at all scales, from initial contact to final modification and adjustment. The fundamental issues for this interpretation are how primary ejecta from basins and craters are distributed; how the deposits vary with distance from the structure; the extent of vertical mixing; how the megaregolith can be geochemically deconvolved to assess the bulk composition of the crust; how the basin, large crater ejecta, and central peak compositions can be used to deduce crustal stratigraphy. Furthermore, well-preserved craters on the Moon provide us with a natural laboratory to understand the impact process and a large range of scales. The intense bombardment of the lunar highlands crust has left little bedrock intact. Thus, to interpret the present surface, it is essential to understand how cratering mixed the original igneous rocks and obscured the original distribution of the products of primary differentiation and subsequent magmatic activity.

Time Phasing (applies to all Investigations):

Early: Map crater and basin geology, compositions, geophysical state, robotic sample return, robotic surface rovers.

Middle: Field study of simple to complex craters (1-10's km); sampling ejecta, melt sheets, bedrock in walls, central uplifts, basin massifs (robotic and human); geophysical profiling.

Late: Field work at large and basin-scaled craters (100-1000's km). Study and sample melt sheets, ejecta, secondaries (robotic and human). Use geophysical profiling the characterize regional scale variations. Search for potential deposits for ISRU in differentiated melt sheets in large impact craters.

Science Priority: High

Rationale: Understand lunar processes and geological history.

Investigation-A: Determine and understand the stages of formation of simple and complex craters, and multi-ring basins

Determine the processes associated with, and the geologic results of, shock, material flow, rim uplift, and, where relevant, the structural uplift of crater floors and modification of crater walls on the Moon. Delineate variations in these processes that are responsible for simple craters, complex central peak craters, complex peak ring craters, and multi-ring basins. Use this structural information to map impact crater units (e.g., central peak and basin massifs) to deduce other properties (e.g., stratigraphy) of the lunar crust and mantle.

Investigation-B: Determine how impacts modify, redistribute, and mix materials

Determine the shock-metamorphism, melting, and mixing of excavated materials in craters of different sizes in different terrains. Likewise, determine the distribution of those materials beyond the crater rim and the mixing of them with other regolith components. These results will provide a baseline for using impact products to assess other properties (like the variable composition) of the lunar crust.

Investigation-C: Determine the origin and evolution of basin melt sheets

Impact theory suggests large basin-forming events may have melted rocks in the lower crust and, possibly, the upper mantle, sampling deeper levels than structural uplifts in craters. Geologic mapping and sample analyses are needed to determine the depth and volume of that melting. These analyses will also provide the information needed to determine how melted portions of the Moon were mixed and how basin melt sheets subsequently evolved, potentially differentiating to form large layered igneous deposits within the crust of the Moon.

Investigation-D: Assess the possibility of impact-triggered magmatism

Determine the composition and age of magmatism within basins and along their margins to determine if large basin-forming events are responsible for some post-impact magmatism.

Investigation-E: Determine the production and evolution of the megaregolith

Determine the volume and distribution of large scale ejecta and impact-reworked crustal units that comprise the megaregolith and distinguish that material from the underlying crust that was structurally disturbed by large subsurface displacements caused by large impact events.

Objective Sci-A-8: Determine the stratigraphy, structure, and geological history of the Moon.

Study and understand lunar stratigraphy on global, regional and local levels. Map the principal units of the Moon, including their geometric shape and distribution, relative and absolute ages, and sequence. Define and study lunar terrains and the time- and rock-stratigraphic units that comprise them. Map lunar structural features and how they interact with stratigraphic units to derive a time history and sequence of lunar tectonism. Determine the geological history and evolution of the Moon.

Time Phasing (applies to all Investigations):

<u>Early</u>: Re-map geology of Moon from new orbital data, robotic sample returns (calibrate remote data), determine relative ages of individual features using crater densities.

<u>Middle</u>: Determine and sample bedrock lithology and structure near lander, robotic sampling of remote sites, geophysical profiling.

<u>Late</u>: Investigate regional units via human field work and robotic reconnaissance, map lateral and vertical extent of units, geophysical profiling.

Science Priority: High

Rationale: Understand lunar processes and geological history.

<u>Investigation-A</u>: Understand the impact history of the Moon

The Moon has been bombarded with debris from the beginning of its history. This impact record was critical not only to lunar history, but by inference to the impact histories of all the inner planets. Determine the impact flux as a function of time, including possible episodicities and periodicities in the cratering rates. Assess the nature and duration of an early cataclysm (if any). Understand the recent flux and calibrate the various relative age scales by deciphering the detailed flux as a function of absolute time. This investigation is very similar to Objective Sci-B-1, but has more emphasis on how the bombardment history has affected the geologic evolution of the lunar crust.

<u>Investigation-B</u>: Determine the stratigraphy of the lunar maria

Determine the sequence, relative and absolute ages, and compositions of the lunar maria, including both lavas and pyroclastics. Map lateral extent and thicknesses of mare color units. Use relative crater densities to distinguish ages. Identify possible sites for sample return and absolute age calibration. Examine and study exposed sections of mare stratigraphy in crater, rille, and graben walls. Sample and date multiple lava flows and dark mantle deposits form around the Moon.

<u>Investigation-C</u>: Determine the stratigraphy of the lunar highlands

Determine the sequence of the earliest units of the lunar highlands, including ancient feldspathic terrain on the lunar far side, the South Pole-Aitken basin floor, and subsequent younger basin materials and interbasin terrains. Map the large craters of the Moon in terms of relative age, with calibration by sample collection and radiometric dating of key selected features. Understand the origins of unusual terrains (e.g., Descartes Formation) and the extent of ancient, pre-Orientale maria. Calibrate the recent time scale and possible recent lunar geological activity (e.g., volatile release, young highland faults) by understanding the flux of very young, rayed craters (e.g., North Ray and younger).

<u>Investigation-D</u>: Determine the tectonic history of the lunar crust

Map the distribution and ages of lunar tectonic features, including both compressional (wrinkle ridges) and extensional (graben) features and determine their ages through their interaction with regional stratigraphic units. Determine the stress history of the crust as a function of time. Determine if the current Moon is undergoing global compression, as suggested by the presence of young thrust faults in the highlands and if so, how much. Assess the strength of the lunar lithosphere by estimating the loading of the crust by mascons.

<u>Objective Sci-A-9</u>: Understand formation of the Earth-Moon system.

Although the consensus is that the Moon formed by the impact of a Mars-sized planetary embryo with the proto-Earth, 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 embryo (and to a lesser extent the primitive Earth), (2) the extent of the fractionation of elements 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, the depth of the magma ocean, 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. This objective requires the investigations discussed under Objective Sci-A-1.

Time Phasing (applies to all Investigations):
<u>Early</u>: Refine estimate of lunar bulk composition from remote sensing and robotic sample return. Heat flow of Moon.
<u>Middle</u>: Sampling of compositionally and geographically diverse lithologies, geophysical network.
<u>Late</u>: Continued sampling of compositionally and geographically diverse lithologies, geophysical network: increase number and density of stations.

Science Priority: High

Rationale: Understand lunar processes and geological history, and provide insight into how planets formed.

<u>Investigation-A</u>: Determine the bulk composition of the crust

Although the crust comprises only about 10 wt% of the Moon, its bulk composition is an important component of the total lunar composition, particularly in assessing the abundances of elements concentrated in it, which geochemists call incompatible lithophile elements (e.g., rare earth elements). Available sample, geophysical, and remote sensing data indicate that the crust is highly variable in composition. This investigation requires determining the compositional layering and thickness of the crust and how they vary laterally.

<u>Investigation-B</u>: Determine the bulk composition of the mantle

The chemical and mineralogical heterogeneity of the crust indicates that the lunar interior is also highly variable in composition. This reflects the combination of primary differentiation and subsequent dynamics, including convection, partial melting, and magma migration and emplacement. Assessing its overall composition (differences between upper and lower mantle, and variation in both between the nearside and farside) requires studies of samples derived from a variety of depths within the Moon. It is particularly important to understand the distribution of volatile elements and water inside the mantle, which can be addressed through studies of volatiles in volcanic deposits and inferring their source regions in the mantle (depth, mineralogy, chemical and isotopic composition). This study includes ejecta from large basins and geophysical measurements.

<u>Investigation C</u>: Determine the early thermal history of the Moon

The thermal history of the Moon has important implications for primary differentiation, the genesis of crustal rocks, and (most importantly for understanding lunar origin) the initial thermal state of the Moon. This investigation is an integration of other investigations coupled with thermal modeling.

<u>Goal Sci-B</u>: Use the Moon as a "witness plate" for solar system evolution.

As the Moon has been tectonically quiet over the last 3.8 Gy, it contains a record of extralunar processes that occurred early in the history of the solar system to the present day. For example, lunar cratering history can be extrapolated to other planets in the inner solar system, its regolith contains a record of solar activity and evolution, and the materials on the lunar surface bear witness to the process of space weathering that can be extrapolated to other airless bodies. In essence, the Moon contains a record of processes stretching back to the first 500 My after solar system formation.

<u>Objective Sci-B-1</u>: Understand the impact history of the inner Solar System as recorded on the Moon.

The Moon retains the history of the early impact environment and flux of the inner solar system, at a time when life may have first arisen on Earth and perhaps Mars. The changes in this impact environment over 4.5 billion years have implications for the evolution of life and potentially for events in the outer solar system.

Time Phasing (applies to all Investigations):
<u>Early</u>: Geological mapping of impact units, relative age dating from remote data, robotic sample return.
<u>Middle</u>: Field study and sampling of geographically and temporally diverse impact targets.
<u>Late</u>: Field study and sampling of geographically and temporally diverse impact targets.

Science Priority: High

Rationale: Use the Moon to characterize the history of the inner Solar System.

<u>Investigation-A</u>: Determine the impact flux during the basin-forming epoch

Characterize the crater production function (i.e., impactor flux as a function of size) for the Moon during the basin-forming epoch and determine the duration of the basin-forming epoch. Was it distributed over the first half billion years of the Moon's history or was the bulk of the basin-forming impact events concentrated in a short period of time approximately 4 billion years ago? This characterization requires quantitative dating of impact basins and ancient large craters. Better understanding of the crater production function during the basin-forming epoch will help calibrate the use of impact ejecta surfaces as chronostratigraphic tools and help calibrate crater counts as a chronological tool, on the Moon and other planetary bodies in the solar system. On Earth, ancient rocks and evidence for early life have been mostly destroyed, but the basin-forming period of impacts may have jettisoned that material to the Moon where it can be found today. This evidence can constrain theories regarding the potential interplanetary transfer of life due to meteoritic exchange between Earth and Mars. Data supporting or rejecting evidence of past life might be obtained without the complicating factor of contamination.

Investigation-B: Determine the impact flux throughout the post-basin-forming epoch

Characterize the flux of impacting bodies in the Earth-Moon system after the basin forming epoch or throughout the past 3.8 billion years. This will calibrate crater counting tools for the Moon and other solid planetary surfaces in the solar system. It will also provide a baseline for evaluating the role of impact cratering in the evolution of life on Earth (and possibly Mars). The Moon is the best available laboratory for such studies.

Investigation-C: Determine the composition and source of impactors

Determine the timing and composition of the impactors that hit the Moon to reveal the source of impacting debris and the mechanisms that generated the flux of debris. The information may define the accretion and early orbital evolution of planets throughout the solar system and elucidate any differences that may have existed in the flux of material to the inner and outer solar system. The data will also provide a measure of the flux of volatile, biogenic, and siderophile elements to the Earth, Moon, Mars, and other planetary bodies as a function of time.

Investigation-D: Characterize the impact hazard to the Earth-Moon system

Determine the properties of the recent flux of impactors to the Moon to evaluate current hazards to the Earth. The record on the Moon is much better preserved than on the Earth, where other geologic processes rapidly erase evidence of the most frequent types of impact events. What is the true rate of impact for objects of different sizes? Is the size distribution of impacting debris different today than it was in the past and, if so, what does that tell us about the mechanisms delivering material to near-Earth space? Do those mechanisms alter objects delivered to near-Earth space in ways that make them stronger or weaker (and, thus, may affect our choice of mitigation techniques for any threatening object)?

Objective Sci-B-2: Regolith as a recorder of extra-lunar processes.

The regolith contains information about the history of the Sun, variations in cosmic ray flux, astronomical events such as supernova and gamma-ray bursts, changing compositions of impactors with time, and possibly even the nature of the early Earth. It is a complicated record, but long-term investigations can shed light on important issues in planetary science and astronomy.

Time Phasing (applies to all Investigations):

Early:	Identify targets for future surface exploration from remote data (magnetic anomalies, paleoregoliths).
Middle:	Precision sampling of regolith at different stratigraphic levels, identify and sample paleoregolith.
Late:	Precision sampling of regolith at different stratigraphic levels, identify and sample paleoregolith at new and wider areas; potential ISRU tie-in for extralunar material search.

Science Priority: High

Rationale: Use the Moon to characterize the history of the inner Solar System and the galaxy.

Investigation-A: Characterize volatile concentrations and their variability

Characterize the volatile phase in the permanently shadowed regions near the lunar poles, and determine the concentration, chemistry, phase relations, temperatures, and geotechnical properties. These volatiles may reveal the chemical nature of impactors on the Moon through time.

Investigation-B: Assess temporal variations in the Sun through studies of solar wind and solar flare products in the regolith

Study the records of past solar particles and irradiance, and galactic cosmic rays preserved in lunar regolith. This work involves searching for identifiable layers of "fossil regolith" that can be dated to track changes in the Sun and galactic cosmic rays through time. This objective is synergistic with use of the lunar regolith as an in situ resource and with use of the Moon as a platform for heliophysics observations. The lunar regolith preserves the composition and flux of solar wind particles over the past ~4 billion years, a record that may elucidate the evolution of the sun and the sources of cosmic rays.

Investigation-C: Assess variability in the solar constant through detailed, long-term heat flow measurements

In principle, borehole temperature measurements can be used to determine the solar constant as a function of time over the last hundreds to thousands of years. Climate reconstruction from subsurface temperatures is a well-developed technique for Earth. Variability in the solar constant is an important input parameter for models of terrestrial paleoclimate.
Time phasing: **Middle and advanced lunar base.**

Investigation-D: Assess variations in cosmic radiation through time

Variations in the dose of cosmic radiation through time, including from supernova, may be recorded in grains in the regolith. This requires detailed sampling and measurements of radiation damage and cosmic ray products in the regolith.

Investigation-E: Search for meteoritic material (including terrestrial debris) in the regolith

The lunar regolith may contain small quantities of materials derived from Earth and possibly other terrestrial planets, delivered to the Moon's surface as planetary meteorites. Samples from the early Earth could provide windows into our planet's early history, including the nature of early life and the composition of the atmosphere.

Goal Sci-C: Use the Moon as a platform for Astrophysical, Heliophysical, and Earth-Observing studies

The Moon provides a unique and relatively stable platform for observations of the Earth, the Sun and the Universe. While distant from the Earth, observatories on the Moon are able to provide important data on Earth's surface, atmosphere and magnetosphere, complementing and enhancing satellite and ground-based observations. 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.

Investigations using the Moon as a platform are described below. They are organized by disciplines, however it should be recognized that overlapping observation requirements and implementation strategies exist and these could be coordinated within and across the science disciplines to maximize the science return.

Additionally, we call attention to the fact that the transportation system being developed by the agency for the return to the Moon will be a tremendous asset for additional science payloads to locations beyond the lunar environment. This particularly applies to opportunities for missions with large aperture telescopes, and capable payloads to other solar system bodies. As an example, an 8-meter monolithic telescope has been suggested for a possible astrophysics mission.

Finally we note that the astrophysical, heliophysical and Earth observing science investigations articulated in this section have not been prioritized relative the broader spectrum of the science of those disciplines. We expect that this roadmap will provide input for consideration in the associated decadal surveys as they are performed.

Objective Sci-C-1: Astrophysical and Basic Physics Investigations using the Moon.

The lunar surface offers some enabling opportunities for astrophysical investigations. Certain applications derive special benefit from lunar surface basing. In general, for telescopes that require frequent oversight, maintenance, and hands-on attention, having such telescopes at an occupied site could be advantageous. But for telescopes that can be largely tele-operated, requiring infrequent repair and or servicing, free space is probably a more friendly place, with regard to thermal equilibrium, power availability, and cleanliness. The lunar surface offers, however, a large platform, a large mass that can be used for shielding, and surface materials that can be used for construction, whether refined or not.

Investigation A: Viewing the Universe and the Seeds of Galaxy Structure in the "Dark Ages"

In this investigation, a large, low frequency interferometer dipole array is used to image the 21cm HI line at $15<z<150$ in absorption against the cosmic microwave background. While this work is being attempted from the surface of the Earth, the far side of the Moon offers enormous advantages. The Earth produces a tremendous amount of radio noise at these wavelengths, both natural, though the geocorona, as well as radio transmissions from communications hardware. On the far side of the Moon, this radiation is largely blocked, and RF noise levels are vastly (at least several orders of magnitude) lower than anywhere else in cis-lunar space in what has been termed the QZM (quiet zone of the Moon). Performance of such an array would be best during lunar night, when the Sun is below the horizon. Several Ares V launch vehicles and cargo landers needed. This work would be very difficult to do in free space, as the lunar surface provides a ground plane that ensures that the telescope only sees in one direction. In order to provide the requisite spatial resolution and sensitivity, the telescope concept consists of a total of several thousand antenna elements spaced out in a 3km area.

<u>Infrastructure Prerequisites:</u>

- Capability to install equipment on the lunar farside, or highly capable correlator hardware that can do signal combining from the antenna elements on-site.
- High speed communication links to Earth from the farside.
- ??kW of continuous power. Power is needed for communications, and tele-operations, and especially for preprocessing of high bandwidth interferometric data.
- Assessment of infrastructure sharing opportunities.

<u>Site Qualification Prerequisites:</u>

- Improved assessment of RF noise as a function of time and farside location; RF noise levels last determined in the 1960s, with primitive equipment, over short time periods.
- Characterization of lunar ionosphere, and possible opacity.
- Assessment of QZM protection and management strategies; as lunar surface is developed, how much radio noise will come with that development?

<u>Development Issues and Trades:</u>

- In-situ fringe preprocessing? Computation speed versus communication speed tradeoff?
- Efficacy of RF noise filtering on the surface of the Earth?
- Architecture of array: individual interconnected dipoles on separate structures, or electrode imprinted unrollable mylar sheet? Deployment strategies?
- Lunar night operation and survival.
- Telerobotic versus human deployment?
- To what extent does required far-side infrastructure introduce the kind of RF noise that the observatory is sited to avoid? What part does far-side development play in the lunar exploration effort?

<u>Possible Precursors:</u>

- A few nearside dipoles. Global signature of Dark Ages, lunar ionosphere.
- Small nearside interferometer for Heliophysics and observations of selected radio galaxies.

Time Phasing:

<u>Early → Late</u>: Precursors needed to establish optimal design. Deployment will require mobility and interconnection. If human oversight required, may require a habitat site.

Science Priority: High. The science from this observatory would be of the highest caliber.

Rationale: Questions this observatory would answer are among the most important astronomical questions. Though extremely ambitious, such an observatory appears to have unique and powerful capabilities.

<u>Investigation B</u>: Probing the Universe at the Highest Energies

In this investigation a high energy electromagnetic and particle detector is proposed that would (1) search for cosmological backgrounds in the diffuse extragalactic gamma-ray radiation, (2) provide dramatically improved sensitivity for GeV emission from short transients such as gamma-ray bursts over that now available, (3) give sensitivity to the relatively weak signals expected from dark matter annihilation in the galactic substructure and from extragalactic sources. In addition, this hadronic calorimeter would provide unprecedented sensitivity to the composition of cosmic rays at and beyond the knee. The observatory would be constructed out of "bricks" of lunar regolith that would act as an absorbing medium. The bricks would be fabricated in-situ, with regolith-miving equipment required for other outpost activities. High precision temperature sensors layered between these bricks would form a tracker-calorimeter. The support structure and 4500 kg of active scintillator would be transported from the Earth to the Moon. In addition the detector would use 145,000 kg of passive material of excavated lunar regolith. The architecture for the telescope has strong heritage from GLAST/FERMI.

<u>Infrastructure Prerequisites:</u>

- Capability to excavate regolith, compress into bricks, and hoist those bricks into a 5 x 5 x 5m cube.
- Capability to deliver and deploy support structure.
- Modest power and communications infrastructure.

<u>Site qualification Prerequisites:</u>

- None.

<u>Development Issues and Trades:</u>

- Optimal structure to support regolith bricks.
- Optimal strategy for regolith excavation and compression.

<u>Possible Precursors:</u>

- GLAST/FERMI has largely proved the general architecture.

> ***Time Phasing*:**
> **<u>Middle</u>**. Deployment requires substantial regolith-moving, and on-site construction effort.
>
> ***Science Priority***: Medium.
>
> ***Rationale*:** Moderate importance. While scientifically important, the observatory may be better put in LEO, as GLAST/FERMI is sited, by a single Ares V. This option needs further study.

<u>Investigation C</u>: Key Tests of the Strong Equivalence Principle in Gravitational Field Theory

Laser ranging between the Earth and Moon provides a direct test of Einstein's theory of general relativity by accurately measuring the shape of the Moon's orbit. Multiple lightweight retroreflectors or transponders located on the lunar surface will increase the existing number of lunar surface targets available to ground-based laser systems, enhancing the long-term evaluation of this foundational physical theory. At present, with Apollo retroreflectors, ranging can be done to within about a centimeter. With better equipment, with optimal spacing, ranging accuracy can improve by two orders of magnitude. For nearly four decades, lunar laser ranging (LLR) has been used to test the strong equivalence principle, which underpins the general theory of relativity. The strong equivalence principle in essence states that the results of all local experiments in a frame of reference in free fall are independent of the motion, and the results are the same for all such frames at all places and at all times. The strong equivalence principle is explicitly required by general relativity but can be violated in other metric theories of gravity, hence measuring SEP predictions with ever-increasing accuracy is crucial to our fundamental understanding of gravity and the search for new physics.

Infrastructure Prerequisites:

- Ideally 5-10 sites over near face of Moon, include with lunar geophysical network.

Site qualification Prerequisites:

- Though not evidently a problem for Apollo retroreflectors, more information about natural dust levitation and deposition could inform reflector design.

Development Issues and Trades:

- Passive retroreflector versus active transponder.
- If active transponder, then lunar night survival strategy, LSSO next gen ranging system.
- Packages will require at least approximately pointed deployment.

Possible Precursors:

- Apollo era retroreflectors are sufficient (<100 kg each).

Time Phasing:
Early. Deployment is simple (proven with Apollo), and just requires visits to well separated sites. Robotic deployment a clear possibility.

Science Priority: High. Essential to include this with future lunar geophysical network.

Rationale: High importance. Best way to answer a fundamental question of relativistic physics.

Investigation D: **Large Telescope at Earth-Sun L2**

Though such a telescope is not lunar surface based, it would rely strongly on Constellation architecture, and in that respect may bear on lunar surface efforts. Ares V can launch 65 mt to Earth-Sun L2, which is understood to be a prime site for astrophysical work, because of the extraordinary thermal stability, opportunity for high performance passive cooling, continual solar illumination, and continual line-of-sight for Earth comm. A related opportunity would be for servicing of such a telescope, to keep functionality and keep the telescope instrumentation at the cutting edge (e.g. as for HST servicing). Such astronaut servicing could be done conveniently by a suitably equipped Orion spacecraft at an Earth-Moon L1 or L2 jobsite, moving the observatory there and back on a low Δv path. Human operations at these Earth-Moon Lagrange points could bear on lunar provisioning and depoting, perhaps with ISRU products, and provide a natural escape route in case of solar storms.

Infrastructure Prerequisites:

- None for launch – Ares V availability is assumed.
- For human servicing, zero-g EVA suits will need development.
- For servicing, stowage strategies for replacement instruments and subsystems in Orion.

Site qualification Prerequisites:

- Earth-Sun L2 is well characterized.

Development Issues and Trades:
- Navigation systems and constellation management at jobsite.

Possible Precursors:
- None required.

Time Phasing:
Early. This is not directly related to the Moon, but requires a heavy-lift launch capability, such as provided by Ares V.

Science Priority: High. Unique capability for high scientific importance, with few additional prerequisites.

Rationale: High scientific importance. In the absence of revolutionary technologies that drastically reduce kg/m2 of mirror substrates, and robotic assembly of large telescopes at a Lagrange point, heavy lift is essential to our hopes for larger, more capable telescopes.

Investigation E: **Ultra high-resolution optical imaging of astronomical objects**

The highest spatial resolution will be achieved using a distributed array of apertures, optically coupled in an interferometer. A 3km baseline interferometer working at optical wavelengths would allow 1AU resolution for targets across our galaxy. This would have huge astronomical value, with moderate sized elements (e.g. 1m). For optical wavelengths, such coupling is just now being achieved on the surface of the Earth with much smaller baselines, but seismic activity, atmospheric perturbations, and thermal variation make the effort extremely difficult. A space interferometer can mitigate these concerns. It has been proposed that a lunar surface array of telescopes will make such optical coupling possible, using the Moon as an optical bench that keeps the apertures precisely phased. Atmospheric perturbations and most natural seismic activity are thus avoided. But for a finite number of apertures at a given lunar site, filling the UV plane for highest quality imaging would require changing the array pattern, and compensation for the track of the target source across the sky. These major operational functions strongly argue for a free-space array which can be reoriented and redistributed freely. Technologies for precision constellation management are becoming understood (e.g. DARWIN), and sites with low external torques (e.g. ES L2) are available.

Infrastructure Prerequisites:
- Major deployment hardware. Cranes, mobility vehicles.
- Major maintenance needs. Many precision moving parts.
- Power, communications, ideally during lunar night

Site Qualification Prerequisites:
- For short wavelength work, natural and induced dust levitation is an important concern. Scattered light a serious issue for daytime operation.
- Dust contamination is also a potential issue for precision fringe and target tracking mechanisms.

Development Issues and Trades:
- Mitigation of day/night and even sun angle thermal instabilities.

- Night survival. Low temperature operation of bearings.
- Induced seismic activity from launchers and vehicular traffic.

Possible Precursors:
- Two-element interferometer with modest baseline could provide proof-of-concept.

> ***Time Phasing***:
> **Late**. Deployment is time consuming, and the array will require regular redeployment for optimal use.
>
> ***Science Priority***: Low. Free space implementation involves some constellation management and formation flying challenges, but these are not insurmountable. Once achieved, telescope operation would be far more flexible than for lunar surface operation.
>
> ***Rationale***: High scientific importance. High spatial resolution addresses many important astronomical questions.

Investigation F: **Detect gravitational waves**

It has been suggested that a precision lateral interferometer be used to measure baselines that could reveal passage of gravitational waves. The 3-element interferometer would be modeled on the terrestrial LIGO facilities, though would have the advantage of not needing an evacuated tube for the beam, and would benefit greatly from the low seismic activity on the Moon. With a several kilometer baseline, 0.256-3Hz gravitation waves would be sampled. This would detect merging neutron stars throughout the nearby universe, and the gravitational wave signature of local group supernovae. The concept is in interesting one, but especially with the increased vibration isolation now being retrofitted on LIGO, accessible frequencies and sensitivity are not unlike LIGO.

Infrastructure Prerequisites:
- Power, communications, ideally during lunar night
- Handling and transport equipment for deployment of ~few hundred kg stations

Site Qualification Prerequisites:
- Dust contamination is also a potential issue for precision fringe and target tracking mechanisms.

Development Issues and Trades:
- Mitigation of day/night and even sun angle thermal instabilities.
- Night survival. Low temperature operation of bearings.
- Induced seismic activity from launchers and vehicular traffic.

Possible Precursors:
- Two-element interferometer with modest baseline could provide proof-of-concept.

> ***Time Phasing***:
> **Middle**. Deployment is time consuming, but once set up, ideally can be left alone.
>
> ***Science Priority***: Low. Recent developments on LIGO should make this Earth-bound facility equally capable.
>
> ***Rationale***: High scientific importance.

<u>Investigation G</u>: Large Lunar Optical Telescope

Lunar-based counterpart of Investigation E. Historically, putting a large telescope on the lunar surface was seen to be advantageous because of the relatively stable surface, and simplification of pointing and tracking such stable surface provided. If associated with an outpost, there would be clear routes for frequent human maintenance and servicing. In fact, pointing and tracking of free-space telescopes is now well understood, and can be done more precisely than for ground based telescopes. The lunar surface involves very significant contamination risks from dust, and lunar gravity, though small, causes deformations in telescopes as they track across the sky. Parts for the telescope require special effort to land and deploy safely. Thermal control is a serious issue, with wide fluctuations in temperature over the lunar cycle. One architecture, that of a liquid mirror, is actually enabled by the lunar gravity, but such a telescope points only at the zenith and is difficult to clean.

<u>Infrastructure Prerequisites</u>

- Deployment hardware – cranes, mobility and assembly vehicles
- Power, comm, ideally during lunar night

<u>Site Qualification Prerequisites:</u>

- Dust contamination is an extremely serious issue for such a telescope.

<u>Development Issues and Trades:</u>

- Mitigation of day/night and even sun angle thermal instabilities.
- Night survival. Low temperature operation of bearings.
- Induced seismic activity from launchers and vehicular traffic.

<u>Possible Precursors:</u>

- Nothing observatory-specific; smaller telescope is of very limited scientific use.

Time Phasing:
<u>Late</u>. Major construction project.

Science Priority: Low. Free space opportunities have much more value.

Rationale: High scientific importance. See above.

<u>Investigation H</u>: Search of exotic stable states of matter.

It has been proposed to use seismic stations space around the Moon to do seismic tomography in order to identify “linear” seismic events that could be consistent with collisions with the Moon of “nuggets” of strange quark matter. The sensitivity and bandwidth of these stations are generally consistent with geophysical needs. Such tomography is most effective when there are a rich collection of stations. At least half a dozen stations, spread all over the lunar surface, are needed for this. This work uses the Moon as a detector, and is essentially impossible on the Earth because of seismic noise. Surface events like meteorite impacts should be easily distinguishable from a quark nugget event that would leave an accoustical trail through the Moon.

<u>Infrastructure Prerequisites:</u>

- Ideally 5-10 sites over near face of Moon, include with lunar geophysical network

Site Qualification Prerequisites:
- None

Development Issues and Trades:
- Lunar night survival strategy, power

Possible Precursors:
- First lunar return geophysical seismic station would verify architecture

Time Phasing:
Early. Deployment is simple (proven with Apollo), and just requires visits to well separated sites. Robotic deployment a clear possibility.

Science Priority: Low. The evidence for such events from Apollo seismometers is mixed, at best, and such particles have not yet been shown to exist. Such an array would best follow up analysis from the lunar geophysical network. In many respects, such a network will already be capable of making these tests, such that a separate experiment is not currently justified.

Rationale: Quark nuggets have never been convincingly identified in accelerators on Earth, so the experiment should not be mounted just to look for them.

Objective C-2: Heliophysical Investigations using the Moon.

Preamble: The Moon is immersed in a plasma environment — the local cosmos — that is "magnetized." It is threaded with magnetic fields that are often "frozen" into the plasma, a state of high electrical conductivity that effectively couples the motions of the plasma and the magnetic field. This inherently strong coupling means that the structure and evolution of magnetic fields (of the Sun, of the Earth, and even of the Moon itself) play an essential role in organizing and regulating the local environment of the Moon — the environment to be experienced by our explorers. By working to understand, and so predict, the variations that occur from day to day, and from region to region, the productivity and overall success of future lunar robotic and manned missions can be significantly enhanced.
The most interesting challenge of the lunar plasma-field environment is that it is alternately dominated by the extended, but variable, outer atmosphere (the "magnetosphere") of the Earth and by the extended, but highly variable, atmosphere of the Sun (the "heliosphere"). The Moon spends nearly 25% of its orbital period immersed within the Earth's magnetosphere, which offers some degree of shielding from heliospheric effects; the remaining time is spent exposed to the full effects of the Sun's radiation and interplanetary fields. Thus, the lunar plasma environment offers unique opportunities to study a variety of fundamental plasma physics processes — processes that have application to many other objects throughout the universe.

In our quest to understand our space environment, our first challenge is to understand the basic physics behind the plasma processes of magnetic reconnection, the mass loading of solar and stellar winds, and plasma-dust interactions. These processes play fundamental roles in the explosive processes at the Sun, and in planetary accretion. Increasingly, as we probe more deeply into the underlying plasma-field interactions, heliophysicists are guided by comparisons of plasma processes in the Earth's magnetosphere, in the solar corona, in the magnetospheres of other bodies in the solar system (the Moon and planets), and in distant astrophysical environments. This comparative approach creates a rich variety of unique opportunities for lunar-based heliophysics science.

With its lack of an absorbing atmosphere, the Moon provides a natural observation platform from which to observe the sky, the Sun, Geospace, and the Earth. Furthermore, the Moon is locked into synchronous rotation with respect to the Earth and therefore always displays the same side to Earth. The Moon has many uses as a platform that would greatly benefit heliophysics.

<u>Traceability to the Heliophysics Decadal Survey:</u> The heliophysics science associated with the return to the Moon is directly relevant to the 2003 Decadal Survey Challenge to understand the basic physical principles manifest in processes observed in solar and space plasmas, and to the 2009 Heliophysics Roadmap Research Focus Area: understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities.

Input from the scientific community regarding recommendations for science investigations associated with the return to the Moon has been distilled into a series of recommended scientific objectives, each with specific science goals and benefits, and implementation considerations. Those objectives are articulated in a report called Heliophysics Science and the Moon (NP-2007-07-80-MSFC, Pub 8-40716):

A. Near-Lunar Electromagnetic and Plasma Environment
B. The Moon's Remanent Crustal Magnetic Fields
C. Magnetotail Dynamics at Lunar Orbit
D. Dust-Plasma Interaction on the Surface & Exosphere of the Moon
E. Imaging the Heliospheric Boundary
F. Low-Frequency Solar and Exoplanet Radio Astronomy
G. Imaging Geospace from the Moon
H. Analyze the composition of the Solar Wind
I. High-Energy Optical Solar Observatory
J. Sun's Role in Climate Change
K. Understand and Predict Space Weather Impact on Robotic and Human Productivity
L. Characterize Radiation Bombardment on the Lunar Surface

The Heliophysics Science and the Moon report team and the NAC Heliophysics Subcommittee subsequently assessed the science objectives of the Moon report by categorizing them into one of four categories:

(1) Compelling science and should be done at the Moon;
(2) Compelling science but better done elsewhere;
(3) Interesting science and should be done at the Moon; and
(4) Interesting science better done elsewhere.

The science objectives that are evaluated to be compelling science and should be done at the Moon fell into three distinct areas of research:

(1) Investigate plasmas near or on the lunar surface including interaction of plasma and dust grains,
(2) Observe radio emissions of solar flares and coronal mass ejections, and
(3) Characterize the radiation bombardment on the lunar surface.

Achieving them will provide the foundational understanding of the "perilous ocean" which spacefaring spacecraft and crews must traverse in order to reach their destinations within the solar system.

These three areas of research are represented by the following 4 investigations that were categorized as being compelling science to be done at the Moon by >75% of the respondents:

- Investigation A. Near-Lunar Electromagnetic and Plasma Environment
- Investigation L. Characterize Radiation Bombardment on the Lunar Surface
- Investigation D. Dust-Plasma Interaction on the Surface & Exosphere of the Moon
- Investigation F. Low-Frequency Solar and Exoplanet Radio Astronomy

Other investigations that were categorized as compelling, whether they are conducted at the Moon or elsewhere, by >50% of the respondents are:

- Investigation B. The Moon's Remanent Crustal Magnetic Fields
- Investigation J. Sun's Role in Climate Change
- Investigation G. Imaging Geospace from the Moon
- Investigation E. Imaging the Heliospheric Boundary
- Investigation I. High-Energy Optical Solar Observatory
- Investigation H. Analyze the composition of the Solar Wind

Note that objectives included in the Heliophysics Science and the Moon report associated with investigating historical record of the Sun, solar wind and the local interstellar medium using the lunar regolith were not considered in the Heliophysical science evaluation since these investigations are being articulated elsewhere in this roadmap.

<u>Investigation A</u>: Near-Lunar Electromagnetic and Plasma Environment
Interaction with the ambient plasma and incident solar ultraviolet (UV) radiation causes the lunar surface to become electrically charged (Manka, 1973; Stubbs et al., 2007a). This creates different and complex environments on the sunlit and shadowed side of the Moon. On the dayside, photoelectric processes driven by solar UV radiation typically dominate, so that the surface becomes positively charged (Singer and Walker, 1962). On the nightside, interactions with ambient plasma electrons usually dominate, leading to the surface acquiring a negative charge (Halekas et al., 2002). This interaction is complicated by variations in solar UV intensity, the characteristics of the ambient plasma, surface composition and topology, magnetic anomalies and the lunar wake, and by the formation of dusty plasmas. In general, the surface electric potential is confined to a near-surface sheath region. The vertical extent of this region, which is controlled largely by the ambient plasma density and temperature, in turn determines the surface electric field strength (Nitter et al., 1998).

Like any object immersed in a plasma, the surface of the Moon charges to an electric potential such that the total incident current is zero (Whipple, 1981). The charging currents come from four main sources:

(1) photoemission of electrons,
(2) plasma electrons,

(3) plasma ions, and
(4) secondary electrons (arising from surface ionization by plasma electrons).

Due to photoionization by solar UV radiation, the lunar dayside typically charges to a few volts positive with a "photoelectron sheath" extending to ~1 m in altitude (Freeman and Ibrahim, 1975). On the nightside, however, interaction with the charged particles in the solar wind leads to surface charging to several hundred volts negative, with a "Debye sheath" extending up to ~1 km in altitude (Halekas et al., 2003). This rudimentary picture comes from application of basic plasma theory to Apollo era and Lunar Prospector observations.

Surface charging is a fundamental universal process affecting all airless regolith-covered bodies, and it is believed to drive the transport of micron-scale dust, a recognized potential hazard for operations on the lunar surface (Stubbs et al., 2007b). In addition, differential charging of objects on the surface could lead to unanticipated electrical discharges. However, here remain significant uncertainties 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. Lunar surface charging in the solar wind is complicated by variations in the solar spectrum, in the ambient plasma environment, in surface composition and topography, by magnetic anomalies, and by the formation of a lunar wake and dusty plasmas. In addition to these effects, when the Moon passes nightside of the Earth, it traverses the tail lobes and plasma sheet of the Earth's magnetosphere. The plasma sheet is much more tenuous and significantly hotter than the solar wind, and observations from Lunar Prospector indicate that nightside potentials can reach a few thousands of volts (negative), both during space weather events and during plasma sheet passages (Halekas et al., 2007). Surface charging processes may be a major driver of the transport of charged dust (e.g., Stubbs et al., 2007b), as observed during the Apollo era (also see section 1.5). The most probable mechanism for dust transport involves the like-charged surface and small (<10 micron) dust grains acting to repel each other. Hazards could arise both due to the differential charging of surface equipment, resulting in unanticipated electrical discharges, and to the transport of charged dust with its adhesive and abrasive properties. Since the lunar surface is an insulator, finding a common ground for electrical systems is much more difficult than on Earth.

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). To optimize the characterization of the lunar plasma environment, it is recommended that measurements from orbit and the surface be coordinated, so that the connection between processes on different scales is understood. 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.

Time Phasing:
<u>Early</u>: Understanding the electromagnetic/plasma environment near the lunar surface will therefore be of benefit both to manned and robotic surface exploration activities and to scientific investigations conducted on the lunar surface.

Science Priority: High.

Rationale: The characterization of the lunar electromagnetic/plasma environment, and the resulting development of dust mitigation technology, permits a sustainable exploration program requiring surface operations, particularly astronaut extra-vehicular activities (EVAs). This study impacts other lunar science activities (e.g., Earth observation, astronomy, and astrophysics), environmental characterization, and operational environmental monitoring. It also paves the way for future missions, for In Situ Resource Utilization (ISRU) activities, and ultimately for the commercialization of the Moon.

<u>Investigation B</u>: The Moon's Remanent Crustal Magnetic Fields

<u>Preamble</u>: The discovery of lunar magnetism was a major scientific surprise of the Apollo program. Solving the enigmas of this remanent field will provide fundamental insights into the thermal history of the lunar core/dynamo and crust, and into the processes of magnetization and demagnetization in large basin-forming impacts. This will require systematic high-resolution mapping of crustal magnetic fields from orbit, surface magnetometer surveys of select regions, and the return of oriented samples.

The Moon does not have an active core dynamo. However, like Mars, it has numerous localized remanent crustal magnetic regions distributed over its surface, with a spatial scale of a few kilometers well below the solar wind thermal ion gyro-diameter, to a few hundred kilometers, large enough to produce shocks for some solar wind conditions (Colburn et al.,1971; Russell and Lichtenstein, 1975; Lin et al., 1998; Halekas et al., 2006). The existence of these regions points to the presence of strong magnetizing fields in the past (Hood et al., 2001; Halekas et al., 2001).
Measurements of remanent magnetism on the Earth provided crucial evidence for sea floor spreading and plate tectonics that led to a greatly increased understanding of the evolution of the Earth's interior and surface. New measurements of lunar and Martian magnetism hold similar promise. Low-resolution orbital mapping by the Apollo 15 and 16 subsatellites and by Lunar Prospector using magnetometers and electron reflectometers shows strong surface magnetic fields in regions antipodal to the large impact basins formed ~3.65–3.85 billion years ago and in some of the ejecta from those impacts. At the same time, the basins themselves are at best weakly magnetized, suggesting that the antipodal magnetism results from shock remanent magnetization (SRM), possibly together with amplification of ambient magnetic fields by plasma produced in the impact process (Lin et al., 1988; Hood et al., 1991, 2001). However, other evidence indicates a quite different source of the lunar magnetic field. Measurements of Apollo lunar samples suggest thermal remanent magnetization acquired in a strong (of order ~1 Gauss) core dynamo magnetic field during the same era (Fuller, 1974).
Resolving these puzzles and understanding the origins of lunar magnetism would provide the basis for unraveling the thermal history of the lunar core/dynamo and crust, as well as the physics of basin-forming impacts. Both these effects are likely to be important for Mars as well.

A focused three-part program, including targeted near surface, high-resolution orbital measurements, surface magnetometer traverses, and laboratory analysis of oriented samples, would allow a determination of the properties of surface crustal remanent magnetization. Knowing the mode of remanent field acquisition (shock, thermal, etc.), and its strength, age, direction, coherence, and spatial scale would allow us to understand the physics of crustal magnetization and the magnetic history of the Moon. Initially (**Early**), a small lunar-orbiting spacecraft with magnetometers and electron reflectometers would provide high spatial resolution mapping of the intensity and orientation of the crustal field by targeting low periselenes (less than ~15 km) over the key South Pole Aitken region and encompassing the strongly magnetized regions antipodal to the Crisium, Imbrium, and Serenitatis basins. Preferably the spacecraft would also measure the nearby demagnetized Orientale basin and two basins with central magnetic anomalies: Moscoviense and Mendel-Rydberg. These measurements would be compared with surface geology in order to constrain the age distribution of crustal magnetism and to quantify its relationship with impact basins, ejecta, and antipodal regions. Later (**Middle**), robotic rovers or humans would conduct magnetometer traverses over selected surface locations. Finally, oriented samples from cores or deep craters would be returned from key antipodal regions, mare basalts, magnetized ejecta, and large impact basins for analysis.

Time Phasing:

Early → Middle: Lunar magnetism provides a powerful tool for probing the thermal evolution of the Moon's crust, interior, and core, as well as illuminating the physics of large basin-forming impacts. Insights into the lunar field will certainly help us understand Mars, which exhibits similar but much stronger crustal magnetism. The same processes will likely apply to other terrestrial bodies and to impact processes in general. Determining the distribution and properties of strong magnetic anomalies will clarify the potential magnetic shielding benefits for lunar bases.

Science Priority: Medium

Rationale: Many strong crustal magnetic anomalies are correlated with surface albedo markings, or "swirls." This strongly suggests that these larger, more intense field regions act as mini-magnetospheres that effectively shield the surface from solar wind ions, and thus may be relevant for lunar base site selection. Furthermore, these varied regions provide fixed plasma laboratories that will allow us to explore interesting and fundamentally different parameter regimes.

Investigation C: Magnetotail Dynamics at Lunar Orbit

Preamble: The dynamical behavior of the Earth's distant magnetotail, where about half of the total energy coupled into the magnetosphere from the solar wind is stored, is completely different from the near-Earth [<30 Earth radii (Re)] tail and is presently not understood. Magnetic reconnection occurs nearly continuously in the distant magnetotail and the reconnection process there is fundamentally different from what occurs elsewhere. Observations around the Moon as it traverses the Earth's distant magnetotail have unique advantages for understanding the physics of this essentially unexplored and poorly understood region.

The energy coupled from the solar wind into the Earth's magnetosphere goes primarily into the formation of a long (>200 Re) magnetotail. In the near-Earth Magnetotail (<30 Re), the stored energy is released in transient substorms, but the distant tail undergoes near-continuous magnetic reconnection. Thus, despite the sparse spacecraft coverage, the Earth's magnetotail provides some of the best measurements possible of the reconnection process (Øieroset et al., 2001, 2002). Magnetic reconnection in the distant magnetotail is physically different (Egedal et al., 2005) from that which occurs in other environments, and it is associated with the acceleration of electrons to energies of hundreds of kiloelectron volts (similar to what is observed for solar flares). Observations in the lunar environment thus provide a probe for fundamental plasma physics and magnetospheric physics. In addition, lunar shadowing of ambient electrons provides a unique and powerful probe of the topology and convection velocity of magnetic fields (McCoy et al., 1975; Lin et al., 1977). The Moon spends ~5 days each month crossing the distant magnetotail, enabling the extensive observations needed to understand the physics. Observations at lunar orbit should also be ideal for studying the dynamics of plasmoids that travel down the Earth's magnetotail after a substorm occurs closer to the Earth.

> ***Time Phasing***:
> **Early → Middle:** Initial (Early) studies would involve detailed plasma, energetic particle, and electric and magnetic field measurements by one or more lunar polar orbiting spacecraft to use lunar shadowing of electrons to uniquely determine magnetic topology and field line velocities. Later (Middle) studies involve arrays of detectors or multiple orbiters at different spatial locations to look at small-scale structures in the plasma. In the long term, the release of barium clouds may be used to trace the plasma flows. This investigation also complements Investigations A, B, and D as well as make observations of the lunar exosphere.
>
> ***Science Priority***: Medium.
>
> ***Rationale***: The study of magnetic reconnection in the lunar environment is an exciting new research area for fundamental plasma physics and magnetospheric physics. Lunar shadowing of ambient electrons also provides a unique and powerful probe of the topology and convection velocity of magnetic fields. Finally, observations at lunar orbit are ideal for studying the dynamics of plasmoids that travel down the Earth's magnetotail after a substorm occurs closer to the Earth.

Investigation D: Dust-Plasma Interaction on the Surface & Exosphere of the Moon

Preamble: The ambient plasma environment and solar UV at the Moon cause the regolith on the lunar surface to become electrically charged (Manka, 1973; Stubbs et al., 2007a). This can result in the electrostatic transport of charged dust (<10 μm) in the lunar exosphere, which has been observed to reach altitudes >100 km (McCoy and Criswell, 1974; McCoy, 1976; Zook and McCoy, 1991) and speeds of up to 1 km/s (Berg et al., 1976). However, the dominant mechanisms that drive this behavior are unknown.

From the Apollo era it is known that dust will have an immediate impact on surface exploration activities and must be addressed to ensure mission success (Bean et al., 1970; Goodwin, 2002). During Apollo, electrostatic processes are thought to have increased the problems with dust, such as adhesion to suits and equipment (Stubbs et al., 2007b). It was also discovered that sunlight was scattered at the lunar terminator, giving rise to "horizon glow" and "streamers" above the surface (e.g., McCoy and Criswell, 1974). This scattering is most likely caused by electrically charged dust grains originating from the surface (Zook and McCoy, 1991; Rennilson and Criswell, 1974). The lunar surface is electrically charged by the local plasma environment and the photoemission of electrons by solar UV. Under certain conditions, the like-charged surface and dust grains act to repel each other, thus transporting the dust grains away from the surface. The limited observation of this phenomenon, together with laboratory and theoretical work, suggest that there are two modes of charged dust transport: "levitation" (Sickafoose et al., 2002) and "lofting" (Stubbs et al., 2006), both of which are driven by the surface electric field. Micron-scale dust is levitated to ~10 cm, while ~0.1-µm dust is lofted to altitudes >100 km. The Apollo 17 Lunar Ejecta and Meteorites (LEAM) surface experiment directly detected the transport of charged lunar dust traveling at up to 1 km/s (Berg et al., 1976). The dust impacts were observed to peak around the terminator regions, thus suggesting a relationship with horizon glow.

All the existing observations of the transport of charged dust were acquired by instruments designed to measure something else (e.g., LEAM was set up to detect hypervelocity impacts). Therefore, it is necessary to make targeted measurements of dust-plasma-surface interactions on the Moon in order to fully understand this alien environment. They can be achieved from orbit to give a global-scale view, or from the surface for a local perspective. To optimize the characterization of this environment, it is recommended that measurements from orbit and the surface be coordinated, so the connection between processes at these scales can be understood. Since not every point on the lunar surface experiences the same conditions (e.g., locations near the poles will be quite different from those nearer the equator), observation from several landers would be advantageous.

Time Phasing:

Early: Characterizing the surface electric field and the electrostatically transported dust's grain size, charge, and spatial distribution, as well as the perturbation of man-made structures to these measurements, is required to provide an understanding of the lunar dust-plasma environment and its impact

Science Priority: High.

Rationale: This work has significant implications for the design and implementation of experiments in other fields, such as astronomy and astrophysics, lunar geology, lunar environmental characterization, and operational environmental monitoring. It will also further our understanding of the environments of other airless bodies, such as Mercury and the asteroids (Colwell et al., 2005). The characterization of this environment, and the resulting development of dust mitigation technology, will permit a sustainable exploration program requiring surface operations, particularly astronaut EVAs. This will pave the way for future missions, ISRU activities, and the ultimate commercialization of the Moon. Horizon glow and other unexplained phenomena caused by the electrostatic transport of lunar dust discovered during the Apollo era hold a great fascination for the general public (Bell, 2006); therefore, this work will also be of great benefit to NASA's Education and Public Outreach program.

Investigation E: Imaging the Heliospheric Boundary

Preamble: The heliospheric boundaries can be imaged in extreme ultraviolet (EUV) and energetic neutral atoms (ENAs) from either the lunar surface or from a satellite in lunar orbit. Due to the sheer size of our heliosphere and the difficulty in observing its boundaries, very little is known about how it interacts with the local interstellar medium. Basic knowledge about the heliospheric boundaries is required to compare our heliosphere with astrospheres of other stellar systems. Such comparisons provide critical information on the current evolutionary stage of stellar winds and stellar mass loss rates, give insight into the stars' local interstellar environments, and possibly enable the assessment of the habitability of other solar systems.

The heliosphere is the three-dimensional magnetic cavity that the magnetized solar wind forms when it expands out into the denser interstellar plasma. At the heliosphere's inner interface, the solar wind plasma slows down abruptly at the termination shock, through which Voyager-1 passed recently at ~94 AU distance from the Sun (Decker et al., 2005). Beyond this region, the solar wind heats up and becomes relatively dense and turbulent in a region called the inner heliosheath (the thickness is most likely 10–100 AU). The final boundary, called the heliopause, separates the outermost extension of the solar wind from the region of space that is completely dominated by the interstellar plasma.

The sheer size of the heliosphere makes remote sensing the only viable strategy for globally imaging these enormous structures that shelter our solar system from the local interstellar medium. To date, there are two promising techniques for imaging the heliospheric boundary: through the detection of Energetic Neutral Atoms (ENAs) and in the Extreme Ultraviolet (EUV):

1) Hydrogen ENAs are produced in the heliosheath through charge-exchange between the shocked solar wind protons and the cold, neutral interstellar hydrogen gas. The shocked protons in this region are mostly isotropic, and some fraction of the resulting ENAs will propagate radially inward, where they can be detected by space-based platforms. The most promising energy range for studying the interactions in the heliosheath is from approximately 0.1 to 6 keV. Although the anticipated ENA intensity from the heliosheath is low, ENA cameras on the Interstellar Boundary Explorer (IBEX) mission have already been designed to meet the requirements of imaging these ENAs with a 6-month exposure time per all-sky image. IBEX is the first dedicated mission that will utilize ENA imaging to remotely probe the heliosheath structure and, thereby, infer fundamental properties of the complex interstellar interaction.
2) He+ ions from the interstellar plasma emit light at 30.4-nm wavelength through excitation by the corresponding solar line, and subsequent reemission. A large increase in number density is anticipated at the heliopause because the interstellar plasma cannot flow across this boundary. Interstellar He+ ions beyond the heliopause would be a sizeable and measurable source of this glow, which provides a way to globally map the heliopause. It has been shown that appropriately designed instruments would be capable of measuring the milli-Rayleigh range intensity of the He+ line with the high spectral resolution required to subtract other EUV contributions. In addition to the He+ emissions from the interstellar plasma, there are also observable sources from the solar wind within ~20 AU from the Sun and the galactic emissions. These can be distinguished from the desired He+ glow by their different spectral and spatial signatures (Gruntman et al., 2005). Due to the enormous size of the heliospheric boundary, variations in its intensity and morphology are anticipated, likely on the order of years.

Time Phasing:

Middle → Late: The deployment and installation of instrumentation on the lunar surface would most likely depend on some level of human assistance. A significant development would be required to achieve a dust-controlled environment.

Science Priority: Low.

Rationale: The structure of the heliospheric boundary, and its implications for other astrospheres, is relevant to astrophysical studies of other stars and beneficial for future missions to the heliospheric boundary. The variations of the heliospheric boundary are on the time scales of years and therefore long-duration observations are also required. The Moon and the anticipated lunar architecture infrastructure provide a platform that meets the instrument requirements (in particular, mass), and, perhaps more important, meets the requirement for long-duration observations. Observatories near the equator on the far side of the Moon would require data downlink through a relay satellite, but would be protected from unwanted terrestrial EUV and ENA emissions. A desired location for lunar deep-sky observations is in one of the deep craters at one of the poles. This location provides an acceptably quiet measurement environment while maintaining a continuous downlink directly to Earth. Since dust scatters EUV and ENAs, the spatial distribution and temporal evolution of suspended or lofted dust layers must be well characterized in order to assess the feasibility of a lunar-based observatory. Satellite based instrumentation in lunar orbit would benefit from avoidance of the dust-related problems and from a much shorter development time, since designs could be based on existing flight hardware. On the other hand, mass constraints would be greater, which would affect geometrical factors and thus sensitivity. The Ares transportation architecture could facilitate orbital observatories such that this investigation might be better conducted from space rather than the lunar surface.

Investigation F: Low-Frequency Solar and Exoplanet Radio Astronomy

Preamble: Radio emissions from solar CMEs and solar flares below 10 MHz can be imaged from the lunar surface in order to probe space from a few solar radii out to 1 AU. Observations of radio emissions from the Sun allow improved space weather forecasting, improve our understanding of shock formation and evolution in the solar wind, and enable detailed time-dependent mapping of the interplanetary electron density and magnetic field topology.

Radio observations of solar activity and solar eruptions have played an important role in understanding the Sun and the Sun-Earth connection. However, the terrestrial ionosphere blocks all radio frequencies below 10–20 MHz. Frequencies below this ionospheric cutoff correspond to all radio emissions originating above 1 to 2 solar radii from the Sun's surface. Natural radio emissions occurring in this enormous volume have been observed only by spacecraft flying outside of the ionosphere. However, single spacecraft are NOT capable of imaging the radio sources. Just like an AM radio, they can detect signals at many frequencies, they can determine their strength, and they can provide some indication of where the radio signal is coming from, but low-frequency radio observations made from a single point cannot be turned into images of the source. Consequently, an image of a solar radio burst at low frequencies has never been made. Even though radio emissions from a CME-driven shock can be tracked without imaging the radio source below the cutoff, there is no way to use the details of the radio emission structure to improve understanding of space weather events or to improve prediction of their potential encounter with Earth or Mars or any other solar system location.

Low-frequency observations from the Moon would open the door on imaging of the regions of particle acceleration in the 2 to 10 solar radii altitudes of the extended solar corona. In this region, the primary radio sources are fast (2–20 keV) electrons from solar flares and suprathermal electrons (~100 eV) accelerated by shocks. The associated radio emissions are called "type III bursts" and "type II bursts", respectively. Both sources produce a plasma instability, which leads to amplification of electrostatic waves, some of which are then converted to electromagnetic (radio) waves. The process takes place at the characteristic frequency of the plasma called the electron plasma frequency; thus, the frequency of the radio emission indicates directly the density of the source, and imaging the radio source would map the extent of the acceleration region.

To make such images at low frequencies, we need to "synthesize" an aperture that is large compared to the wavelengths in question. Large arrays are required to provide the desired angular resolution. An angular resolution of 1 degree at 1 MHz requires a minimum diameter of 15 km. The design for the first (test) array would be based on the designs of Earth-based arrays (working at higher frequencies) currently in development. Subsequent deployment of each phase of the observatory would be carried out after several years, permitting one to maximize lessons learned from implementing each phase.

In addition to images of CME and other solar-related radio emissions, nearly identical equipment could also be used to greatly improve our understanding of the magnetized planets. Earth, Jupiter, Saturn, Uranus, and Neptune all have their main nonthermal emissions from their auroral zones below 10 MHz. Also, imaging emissions from galactic and extragalactic objects in this low-frequency range would open a new window in astrophysics, since there are essentially no existing observations of these objects. In this frequency range, many steep spectra objects like pulsars should dominate the sky and background emissions should exhibit important absorption modifications of the spectrum.

Time Phasing:

Middle → Late: An array ≥ 15 km diameter can most efficiently be implemented on the Moon in a phased approach, such as:

- Initial test array of 16–32 elements, operated at a number of fixed, narrow-band frequencies, with data downlink to Earth of ~8 Mbps;
- Increasing the size of the array by adding elements. This yields higher angular resolution and better imaging capability. The increased data volume would require more sophisticated onsite data processing to keep the Earth downlink requirement to a reasonable data volume;
- Implementing a second array, to provide full-sky coverage. This array would likely be located on the far side of the Moon, requiring a data downlink relay. An additional advantage of the lunar far-side location is that all interfering terrestrial radio noise is blocked by the Moon.

Science Priority: High.

Rationale: The Moon offers a large, relatively stable surface on which to build a large, capable, low-frequency radio array, for the purpose of imaging solar, heliospheric, and other astrophysical sources at wavelengths that cannot be observed from the Earth's surface.

Investigation G: Imaging Geospace from the Moon

Preamble: Photon and particle imaging of geospace, the extended region around Earth that includes the ionosphere and magnetosphere, can be accomplished from the lunar surface or from free-flier spacecraft. Such imaging can address several compelling science questions related to large-scale coupling mechanisms between various complex regions in Geospace from the ionosphere and extending into the magnetosphere.

Global observations of ionospheric and magnetospheric phenomena provide measurements that are key to understanding the hazards and impact of space weather in the regions of space where most space agency, commercial, and military space operations occur. These measurements also provide constraints to global ionospheric and magnetospheric models and provide keys to solving compelling science questions associated with the coupling between the solar wind, magnetosphere, and ionosphere and coupling of the high and mid-equatorial regions of the ionosphere (Meier, 1991; Su et al., 2001).

Imaging of geospace with optical Ultraviolet (UV), Extreme Ultraviolet (EUV), and Energetic Neutral Atom (ENA) instruments from the lunar surface, from lunar orbiting, or from free-flier spacecraft can address several compelling science questions. These include, but are not limited to: large-scale coupling mechanisms between various regions in geospace from the ionosphere and extending into the magnetosphere (using UV and EUV global images); mesoscale coupling between high, mid, and equatorial regions of the ionosphere (UV images and spectral signatures); largescale magnetospheric configuration during magnetically disturbed periods (UV, EUV images); development and evolution of ionospheric disturbances that impact communications and GPS signals (UV images); and ring current and plasma sheet dynamics (ENA images). Lunar surface operation enables new opportunities for enhanced communication bandwidth, instrument "staring," and simplified subsystem design owing to the simplicity of fixed site operation when compared to a free-flier.

Far ultraviolet remote sensing from the Moon offers the means to observe the signatures of the energetic and dynamical properties of the ionosphere/thermosphere (IT) system (Carruthers and Page, 1972). The lunar vantage point allows nearly every point on the Earth to be examined at all local solar times during each month, thus removing seasonal effects. Designing a sensor with a spatial resolution of 10–100 arcseconds is well within our current capabilities. Such a sensor would provide real-time IT specification as well as addressing key, driving science questions about the response of the IT to geomagnetic and solar disturbances. Other sensors could readily be envisioned such as those capable of imaging the geocorona (Carruthers et al., 1976) and the plasmasphere. It may even prove practical to image the polar outflow signatures of some ions.

There are many benefits to imaging geospace beyond advancing knowledge and understanding of this complex coupled region, such as:

- The identification and specification of ionospheric structure and irregularities that impact GPS signals, at all scales from 25 km to thousands of kilometers.

- The identification and tracking of changes in composition that affect the amount of drag seen by satellites in low Earth orbit.
- The identification of the location of the equator-ward edge of the aurora for radio frequency propagation (for both civil aviation and over-the-horizon radar applications).

> ***Time Phasing***:
> **Early:** Could occur Early if deployed in lunar orbit by the Ares transportation system.
>
> ***Science Priority***: Low (from the lunar surface).
>
> ***Rationale***: There are two types of geospace imaging missions that will be enabled by missions to the Moon: (1) those that can best be done from the surface and (2) free-flier or lunar orbiting missions that are enabled by the journey to the Moon. While the lunar surface provides a seismically quiet, largely jitter free platform for the observation of geospace via remote sensing, such observations could be better achieved from lunar orbit, with sensors being deployed by missions en-route to the Moon.

Investigation H: Analyze the composition of the Solar Wind

Preamble: The solar wind reflects the composition of the Sun and physical processes in the corona. Analysis will help differentiate between several theories of solar system formation and physical processes in the solar corona. Ions will be collected on various materials and analyzed on return to Earth. For a good overview, see Wiens (2004) and Geiss (1972).

It is believed that the highly diverse objects of our solar system originated from a relatively homogeneous solar nebula. Ultimately, the correct theories for the origins of these objects, including planetary atmospheres, will be validated by their predictions of chemical and isotopic compositions relative to the average nebular composition preserved in the surface layers of the Sun.

The basic feasibility of an experiment to address this issue has been demonstrated by the short (2–40 hour) exposures of foils during Apollo missions and by the Genesis mission in 2001–2004. Foils were flown on Apollo 11, 12, 14, 15, and 16. The mass for Apollo 16 was 450 g for a foil that was exposed for 45 hours. Net exposure times of several weeks to months were achieved during the Genesis mission. However, much longer exposure times to the solar wind are needed to provide sufficient data to achieve the science objectives.

The proposed investigation provides solar abundances at the level of precision required to discriminate among competing theories. Moreover, the experiment will test fundamental assumptions, such as whether or not solar and nebular compositions are identical. The experiment will return solar matter for compositional analysis in terrestrial laboratories. Ultra-pure materials, such as those utilized on the Genesis mission, will be exposed to the solar wind for varying periods, under varying solar wind conditions, and at different parts of the solar activity cycle. Average and near-instantaneous solar system isotopic and elemental compositions will be obtained. Samples will be analyzed when returned to Earth. The associated laboratory analytical instruments will be patterned after those established for the Genesis samples.

Time Phasing:

<u>Middle</u>: These instruments can be set out on the lunar surface, either robotically or by humans. They should remain deployed for months to years, be recovered, and then be returned to Earth. Recovery is probably best done by humans, rather than robotically, in order to assess the condition of the instruments and their environment. Experience has already shown, via Apollo and Genesis, that robotic deployment is feasible and relatively simple.

Science Priority: Medium.

Rationale: May only provide incremental science as the analysis of Genesis samples is continuing.

<u>Investigation I</u>: High-Energy Optical Solar Observatory

<u>Preamble</u>: The Sun can be observed with optical and UV telescopes and coronagraphs, vector magnetographs, and x-ray and gamma-ray imaging spectroscopes from the Moon.

Solar flares and CMEs are the most powerful explosions in the solar system. Over a period of minutes, they accelerate copious quantities of electrons, protons, and heavier ions (Miller et al., 1997). Although the physical processes by which this is achieved are not fully understood, the general scientific consensus is that the energy originates in stressed coronal magnetic fields and is released through a process known as magnetic reconnection. Understanding the processes through which magnetic energy is converted into accelerated particles is fundamental to understanding particle acceleration in general, and in particular, in planetary magnetospheres and in other astrophysical sources.

Larger flares are usually associated with CMEs that propagate outwards into the interplanetary medium, producing shock-accelerated particles at their leading edges (Zank et al., 2000). Both particles accelerated directly in the flare and those produced by the CME can have devastating effects on spacecraft instrumentation and on astronauts who are not adequately shielded. The electric and magnetic disturbances caused by the interaction of the CME with the Earth's magnetosphere can create havoc on terrestrial communications and power networks (Joselyn, 1992).

Therefore, the benefits of undertaking this investigation are hence twofold:

1) Enable fundamental advances in our scientific understanding of the processes that lead to energy release and the acceleration of energetic charged particles by the Sun and hence in other, more distant and more energetic, astrophysical objects; and
2) Allow us to further our understanding of the conditions that lead to hazardous eruptive solar events, and hence to provide operationally useful warnings (or "all-clears") to enhance the safety and productivity of manned missions to the Moon and Mars (see Introduction to the Feed Forward Theme).

A return to the Moon will permit the construction of telescopes and instrumentation designed to observe the high-energy emissions produced by the Sun during flares and other eruptive events. Although many of the necessary observations can be carried out using free-flying instrumentation, there are some significant advantages to deploying such instrumentation on the lunar surface:

- Observing from the Moon will permit us to extend the energy range of solar (and cosmic ray) spectra below the energy cutoffs imposed by the Earth's atmosphere and also permit observations to be made free of complicating geomagnetic effects and the day/night observing cycles in all but Sun-synchronous Earth orbits.
- The Moon, because it is seismically quiet (relative to Earth) and has no wind, provides an exceptionally large and relatively stable platform on which to position observing instrumentation.
- Deploying instrumentation near the "peaks of eternal light" at the lunar South Pole permits a continuous, unobstructed view of the Sun with relatively constant background. Instrumentation deployed at sortie sites would also be able to observe the Sun for half a lunar day, i.e., ~14 days. Coincidentally, this is also half the solar rotation period, so that a long-lasting solar active region could be observed uninterrupted by night or increases in background from its first appearance over the East limb to its disappearance over the West limb some 13 days later. Much of this time would be when the region is most strongly connected magnetically to the Earth-Moon system and so presents the greatest hazards to communications, space-borne instrumentation, and astronaut health in the near-Earth space environment.
- The slow rotation rate of the Moon also allows horizon occultation measurements (at a drift rate ~0.5 arcseconds/second) to be made at nonpolar sortie sites. This would permit the study of fine-scale features in solar active regions.

Together, this complement of instruments will permit a thorough study of the magnetic precursors to solar eruptive events, the particle acceleration processes that occur within the flare itself and at the CME-associated shock, and the relationship between solar conditions and the probability of hazardous particle events at 1 AU. During certain times of the year (depending on planetary alignment), it will also provide important diagnostic information on active regions that pose a hazard for spacecraft en route to, and orbiting, Mars.

To provide nearly continuous coverage, some or all of the instrument packages could be replicated and reside near opposing limbs of the full Moon within contact of ground stations on Earth, thereby enabling quasi-continuous monitoring of solar activity.

Because of the need to transport such instrumentation to the Moon on a lander spacecraft, typical instruments would have dimensions comparable to those on Earth orbiting unmanned spacecraft, viz. size from <1 m to ~10 m and mass in the range of 10 kg to 1000 kg. However, these values could be extended through lunar surface assembly of modular subcomponents (e.g., interferometer components). The instrumentation would need <1 kW of power to operate. The large data collection rates (in excess of 10–1000 GB/day) could be accomplished through in situ storage for collection by astronauts on EVA activity and subsequent return to the Earth.

Time Phasing:

Middle → Late: Human involvement is necessary to put the instruments in appropriate locations and possibly to retrieve data on a periodic basis. Real-time analysis of the data to provide operationally useful products will require the presence of a trained scientist-astronaut.

Science Priority: Medium.

Rationale: The experiential learning earned during lunar missions will be invaluable for later Mars missions, when real time risk evaluation and operational decisions will have to be made by the crew on the Martian surface independent of ground control at Earth. This investigation will also play a major role in safeguarding astronauts and spacecraft from radiation hazards associated with violent solar activity through the ability to develop real-time reliable forecasting of hazardous radiation events

Investigation J: Sun's Role in Climate Change

Preamble:
The whole Earth reflectance is measurable from the Moon for the full range of reflection angles through each lunar month.

In general terms, Earth's climate is driven by the Sun's output, the Earth's reflectance, and thermal emission. Of these three fundamental climate variables, the Earth's reflectance is the least well studied. In fact, variations in reflectance are being implicitly ignored when solar cycle variables are treated as proxies for the net sunlight reaching Earth. Currently, the value of Earth's reflectance is a combination of localized measurements and modeling. By measuring the reflectance from the Moon, one can obtain a value for the whole Earth each 24-hour period, and through the lunar month, one can measure the reflection as a function of phase angle. These earthshine observations would provide the most thorough and complete measurements of the Earth's reflectance and its seasonal changes, as well as its longer term evolution. This investigation is focused on providing important information needed to fully characterize global climate change and the Sun's role.

Variations in the solar irradiance have been precisely measured for more than a quarter century, combining observations from various satellites, and it appears that the Sun's irradiance has climatologically insignificant variations over the solar cycle. These observations do not explain the terrestrial signatures of the solar cycle in climate records. If the recent irradiance variations are typical, the logical effect to search for is a corresponding, or even amplified, solar driven change in the much less well-studied reflectance of the Earth. Answers here require precise measurements of the global reflectance of the Earth. Several indirect mechanisms have been proposed in the literature to produce such amplification, ranging from changes in EUV radiation tied to ozone, to changes in cosmic rays and atmospheric ionization tied to cloud formation, to changes in storm tracks and atmospheric circulation, or changes in the Earth's global electric circuit. But, so far, the possible causal role of each mechanism remains ambiguous, at best.

Ideally, to determine the Earth's reflectance, it would be necessary to observe reflected radiances from the Earth, from all points on the Earth and at all angles. An Earth-facing part of the edge of the Moon would provide an ideal platform from which to measure the Earth's reflectance. To determine the Bond albedo (reflection in all directions) from earthshine, one would integrate over all phases of the Moon and get a large-scale value for the parts of the Earth contributing to the earthshine. Measuring the resolved earthshine would provide the reflectance for small patches of Earth, which would be of central importance in climate modeling. At present, there is difficulty in treating clouds in climate models, and it is the behavior of clouds that the Intergovernmental Panel on Climate Change (IPCC) says is the greatest uncertainty in climate modeling. The resolved earthshine would provide direct measure of local reflectances/cloud cover. These observations would be an excellent complement to data from satellites in LEO, where determining albedo from the measured radiances is more complicated, because modeling of bi-directional radiative transfer through the atmosphere is required, and that has its own difficulties.

Time Phasing:
<u>Early → Middle</u>: The instrumentation could be set up robotically or by humans, but observations need to be made for years.

Science Priority: Low.

Rationale: While the Moon provides a unique platform from which to measure the Earth's reflectance in both high and low resolution, as well as the entire spectrum of solar output from hard x-rays to the infrared and from the various components of the solar wind, these observations could be better made from orbital assets.

<u>Investigation K</u>: Understand and Predict Space Weather Impact on Robotic and Human Productivity

<u>Preamble</u>: Space weather impacts the productivity of human and robotic explorers. Understanding and being able to predict space weather and associated impacts will mitigate operational risks at the Moon. Steps to achieve this include:

- Use the coordinated, distributed, simultaneous measurements provided by the heliospheric great observatory to drive predictive models of space radiation at the Moon;
- Use real-time measurements on the Moon to account for the effect on the local environment of the anisotropy in solar particle events and for redundant nowcasting of space weather;
- Use real-time measurements on the Moon to determine the radiation hazards, the electrodynamic plasma environment, and effects of dust dynamics and adhesion;
- Characterize the dust environment at several locations on the lunar surface to better understand the operational environment of the Moon.

Mitigating the exposure risk requires the delivery of reliable operational products, based on monitoring of hazardous radiation, to mission operators, planners, and crews. It will also require a dedicated effort to generate near real time operational data that are supported by a fundamental understanding of the underlying physics. The infrastructure to monitor space weather over timescales of days to hours to even minutes exists.

The Moon's tenuous exosphere is immersed in the plasma and energetic particle environment of the heliosphere. The hazardous radiation from intense SEPs arises from solar events such as flares and CMEs generated through the dynamic and often explosive reorganization of intense magnetic fields at the Sun. CMEs plow through the solar wind, forming shocks, which, in turn, accelerate protons to

energies typically in the range from less than 50 to 1000 million electron volts. These high-energy protons interact with the material of spacecraft, the components of the spacecraft control systems, space habitats, space suits, and human tissue. In doing so, they produce dangerous secondary particles that can cause radiation effects in spacecraft electronics and damage DNA throughout the human body. In humans, the radiation can produce acute effects such as sickness, fatigue, and damage to the skin and eyes, as well as chronic effects including cancer, damage to the central nervous system, cataracts, and heart disease (NCRP Report No. 153, 2006). To mitigate the harmful effects of radiation, the heliophysics science community is advancing its understanding of the sources of particle radiation and developing predictive models of the solar and Heliospheric phenomena that generate this radiation.
At present, we do not fully understand the mechanisms that trigger CMEs or solar flares. We have preliminary models of energetic particle acceleration at the shocks driven by CMEs, but these models are still primitive in their predictive capabilities. Current and future Science Mission Directorate (SMD) missions will attempt to fill holes in our understanding, paving the road to predictive models of space weather. The current Solar Terrestrial Probe (STP) STEREO and Hinode (Solar-B) missions, the future Living With a Star (LWS) Solar Dynamics Observatory (SDO) and Radiation Belt Storm Probe (RBSP) missions, and the Solar Sentinels mission concept may help develop the physical understanding necessary to reliably model and predict the radiation environment at 1 astronomical unit (AU) and understand the dominant mechanisms associated with the energization of particles that produce harmful radiation. This information will then be used to specify the physics-based space environment models that will be driven by coordinated, distributed observations from a space monitoring system (Baker et al., 2006). The targeted outcome is reliable predictions of space weather in support of human and robotic mission operations in the lunar environment. This network of coordinated space weather observations and models is a first step for the more comprehensive forecasting needed to support missions to Mars.

The highly variable plasma environment at the orbit of the Moon is due both to the changing conditions of the impinging solar wind and traversals of the Earth's magnetosphere. (Stubbs et al., 2007a) The Moon can enter the hot and tenuous plasma sheet in the Earth's magnetotail, causing increased electrostatic potentials. The resulting surface charging can drive the electrostatic transport of charged lunar dust. The lunar dust-plasma is highly susceptible to space weather. Therefore, observations of the dust-plasma environment during a range of different solar and magnetospheric activity conditions are needed. A space weather monitoring system using the Moon as a platform can provide redundant actionable information for mission management.

The interaction of solar wind and energetic particles with the lunar surface produces large surface electric fields (analogous to spacecraft charging). The electric fields were remotely sensed by Lunar Prospector (Halekas et al., 2005a). The lunar surface potentials are large (up to many kilovolts negative on the night-side hemisphere that is immersed in hot energetic plasma). In sunlight, where photoemission dominates, the lunar surface potentials are typically a few volts (positive). This large potential difference at the day-night terminator causes very large electric fields, with associated hazards to astronauts and equipment, and these fields affect the transport of charged dust grains on the lunar surface and in the tenuous lunar atmosphere. The charged dust grains pose significant hazards to machinery and lunar inhabitants; the nature of this dust hazard depends on the properties of both the lunar plasma environment and the dust grains. The electrostatic plasma-dust interactions are complex, often mitigated by SEP events (Halekas et al., 2007), and are neither well characterized nor well understood.

The colliding solar wind produces an ion-free cavity behind the Moon, but solar wind electrons traveling along the magnetic field (which is generally not parallel to the solar wind) can enter the cavity. Very large charge separation electric fields, critical to kinetic-plasma interactions, are produced at the solar wind terminator, and these in turn produce a variety of intense plasma waves and beams.

Time Phasing:
Early → Middle: Measurements of space weather phenomena provide direct input to predict the effects on the lunar dust-plasma environment and information for mission management.

Science Priority: Medium.

Rationale: This science is of high intrinsic value because developing such a predictive capability requires the solution of many as yet unsolved and longstanding problems in heliophysics. Deployment of onsite resources that will accurately measure the local radiation environment will be invaluable in the event of geocommunication disruptions, when lunar inhabitants must rely only on local resources to manage their radiation exposure (Neal and Townsend, 2001). Onsite measurements would also provide direct input to predict the plasma and electrodynamic effects on the lunar dust environment, and provide a redundant forecasting capability and training for future Mars missions. The current SMD Solar Terrestrial Probe (STP) STEREO and Hinode (Solar-B) missions, the future Living With a Star (LWS) Solar Dynamics Observatory (SDO) and Radiation Belt Storm Probe (RBSP) missions, and the Solar Sentinels mission concept, makes this a medium Science priority for the lunar surface.

Investigation L: Characterize Radiation Bombardment on the Lunar Surface

Preamble: The overarching goal is to characterize the radiation bombardment on the lunar surface and subsurface in order to better understand the operational environments on the Moon, to validate and improve radiation models, and to improve our understanding of the radiation environment of Mars. We describe here a scientific investigation to study, characterize, and monitor the lunar radiation environment by understanding the effects of solar activity, radiation from extra-solar sources, and induced radiation from the lunar surface on the operational environment.

The radiation environments at the Moon and Mars originate from GCRs and the solar particle events (SPEs). The primary effects are total radiation dose (dominated by protons) and single-event effects in electronics (due principally to ions with higher atomic numbers). The total dose and effects from individual, highly-ionizing particles are important for both the human component and the electronic systems components of long-duration lunar missions, as the crew will depend on the health of both for a successful mission.

In addition to the primary, incident radiation, one must consider the lunar albedo radiation (principally neutrons) produced by the interactions of GCRs and SEPs in the surface. The neutron albedo can contribute as much as ~18% to the effective dose received by crewmembers when the radiation environment is dominated by GCRs. When SEPs dominate, the neutrons contribute ~2% to the total dose (Adams et al., 2007b). The case for Mars is more complex because the Martian atmosphere attenuates GCRs and SEPs observed at the surface, but atmospheric nuclear interactions generate neutrons, adding to the albedo from the surface (Saganti et al., 2004). Therefore, secondary neutrons make a larger contribution to the environment at Mars. Prediction of the environment in subsurface or shielded locations on the Moon and Mars relies on radiation transport codes. These codes (Townsend, 2005; Tweed et al., 2005; Andersen et al., 2004; Townsend et al., 2005) require models of the relevant nuclear fragmentation crosssections and knowledge of the energy spectra (composition and distribution in energy) in the radiation environment.

During the onsets of some SPEs, the highest energy (>100 MeV) particles exhibit a large anisotropy as they stream along the interplanetary magnetic field (S´aiz et al., 2005). The anisotropy, combined with the shadowing effects of the entire Moon and local topography, can lead to differences in the actual exposure to lunar-based assets when compared to interplanetary measurements. While these shadowing effects are expected, their details have not been quantified nor modeled, thus emphasizing the importance of monitoring the radiation environment at the locations of interest.

This investigation will address the radiation environment outside a solid body (space vehicle, Moon, or planet) and address the interactions of that environment with nearby material. The specifications of the outside environment, coupled with better models of the interactions with matter derived from both ground-based testing and measurements at the locations of interest, are necessary for applying our knowledge to future landing sites such as Mars and longer duration missions anywhere in the heliosphere.

Time Phasing:

Early: Results of this investigation, plus an understanding of the biological effects of this environment, will enable the creation of specifications for radiation shielding, mitigation techniques, and countermeasure strategies.

Science Priority: High

Rationale: Appropriate radiation mitigation techniques are essential for ensuring crew health and the prevention of instrumentation malfunctions during extended stays on the Moon. These measurements will be used to improve and validate predictive radiation transport models.

<u>Objective C-3</u>: Use the Moon as a platform for Earth-observing studies.

<u>Preamble</u>: The goal of NASA Earth Science research is to observe, understand, and model the Earth system to: (1) monitor its processes and discover the way changes occur; (2) enable accurate prediction of these changes; and (3) understand the consequences for life on Earth. Currently, the space-based data used for this research is gathered from instruments in low Earth orbit (LEO) or geostationary orbit (GEO). With a return to the Moon, NASA is in a position to enable a relatively stable, longer-lived Earth viewing observatory, the data from which would address a range of Earth-science issues over time; provide instrument synergy among multiple LEO and GEO satellites for cooperative operations and enhanced calibration/science; as well as provide views of the Earth's surface and numerous limb occultation opportunities not obtainable from either LEO or GEO.

The lunar surface offers a relatively stable, serviceable platform for global, continuous, full-spectrum monitoring of the Earth over a long time scale, which allows a broader suite of instruments to be deployed and upgraded. The rotation of Earth as seen from the Moon, provides unprecedented temporal views of transient phenomena such as natural hazards, pollution, climate change, and vegetation/land surface changes. Unlike LEO/GEO-based instruments, an instrument suite on the Moon could be serviced/upgraded to provide long term measurements at a reduced cost. And unlike GEO instruments, only one instrument is required on the lunar surface (or positioned at the lunar L1 point) to image the Earth. Furthermore, the Earth's orbital precession allows full observations of the polar regions, which are not observed with either GEO or LEO satellites, enabling measurements of the variability of large ice sheets, glaciers, and sea ice.

A lunar based Earth observatory could be implemented using a phased approach from relatively simple instruments deployed by robotic or human sorties to the surface to more complex instruments housed within a permanent observatory (or at sortie locations on the lunar near-side) with near-full views of the Earth. These imaging opportunities also provide a critically-important education and public outreach (E/PO) opportunity operating in the most simplistic form as a *Blue Planet Webcam*, which would allow anyone one Earth to observe their planet. In a more complex application, the data from the possible instrument suite would be vital for climate change studies and compiling integrative spectral datasets that could be used for future planet finder missions, for example.

However, an Earth observatory on the Moon is also limited due to the potential viewing restrictions at a south polar site. In addition, the dusty lunar environment could hinder optical observations that rely on larger telescopes. Finally, the instruments eventually housed in this observatory must be complementary to the goals of the larger Earth Science community, which are represented by Decadal Survey now being implemented.

<u>Traceability to the Earth Science Decadal Survey:</u> The first comprehensive Earth Science Decadal Survey (ESDS), *"Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond"* was published in 2007. The document does not specifically address Earth observations from the Moon nor does it give specific recommendations for the time period after 2020. Presumably, this would be the time frame of lunar operations as well as the next ES Decadal Survey. The document does specify overarching recommendations for NASA and NOAA and recommends 17 specific missions (14 NASA, 2 NOAA, 1 shared). These missions are divided into three time periods (2010-2013, 2013-

20-16, 2016-2020) and three cost estimates (< $200 million, $200-$600 million, > $600 million). Many of the identified investigations below could serve to directly address the science goals of several of the 17 ESDS missions or indirectly address those goals by complimenting future LEO/GEO missions. Specifically, the ESDS-specified missions traceable to the lunar-based Earth Science investigations are:

Investigation:	**ES Decadal Survey proposed missions:**
• **B:**	*GEO-CAPE, GACM, GPSRO, PATH*
• **C:**	*CLARREO, SCLP*
• **D:**	*HyspIRI, SCLP*
• **E:**	*HyspIRI, GEO-CAPE, GACM, PATH*
• **F:**	*XOVWM, SMAP, DESDynl, SWOT, LIST, PATH*
• **H:**	*all of the above*

Crosscutting Recommendations: There are several trade studies/activities that apply to all the Earth Science investigations. These should be considered prior to the planning of the initial Earth Observatory Demonstration investigation *(see investigation H below)*.

- Scientific input needed for the eventual Earth Observatory location
- Continued evaluation and prioritization of science investigations
- Integration with the current Earth Science Decadal Survey (ESDS) *and beyond*
- Lunar architecture should enable highest priority investigations
- Lunar transportation should have a capability to deploy small payloads into lunar orbit (e.g., Earth-Moon L1 point)
- Options for human and robotic sortie missions must be conducted
- Roles and capabilities for astronauts (scientists) must be defined

Infrastructure/Site Location Prerequisites: The following infrastructure prerequisites apply to all Earth Science investigations listed below:

- A suitable surface location must be identified that: (1) provides desirable Earth viewing (> 90% of the time), (2) minimize dust contamination, and (3) allows future servicing/repairs/upgrades during human or robotic sorties
- Specifics need to be resolved on how these studies might compliment/integrate with observations obtained from LEO/GEO satellites
- Assessment of infrastructure sharing opportunities
- In general, high-resolution large telescopes are not needed, most science requirements can be met with ~ 30-50 cm telescopes (unless otherwise noted)

<u>Investigation A:</u> Characterize the lightning distribution of the whole Earth disk

The most intense electrical storms on Earth result in approximately 60 deaths/year in the United States, but about 24,000 deaths/year globally. This number is expected to rise with increasing population and the potential of more intense storms due to climate change. Lightning is also estimated to produce 6 Tg/year of NOx (~ 15% of the global production). Observations of lightning discharges can help to resolve the tropospheric coupling to middle atmospheric phenomena such as Sprites, Jets, Gamma Ray Bursts, etc. The future GEO-based Geostationary Lightning Mapper (GLM) instrument on GOES-R (2014) is designed to detect many of these, but will be limited in its global coverage. A lunar-based lightning imager would provide a global climatology of lightning activity with more extensive observations throughout the diurnal cycle than is currently possible or even will be possible a decade from now.

> ***Time Phasing***:
> **Middle → Late:** with current technology and the desired resolution, an instrument would require a larger (1 m) telescope and a suitable Earth viewing location.
>
> ***Science Priority***: Medium
>
> ***Rationale***: important observations with direct societal impact (e.g., severe storm onset, improve airline routing, linkages to wild land fires, air quality) and will compliment future LEO/GEO sensors. Lunar platform will enable a larger Earth viewing area as well as near continuous observations.

<u>Investigation B</u>: Monitor the Variability of Earth's Atmosphere

Atmospheric chemistry/plume transport can be derived from lunar-based instruments acquiring both limb and full-disk Earth measurements. These data will further compliment current/planned LEO measurements. Observations could include the monitoring and forecasting of air quality (e.g., ozone, aerosols), the monitoring of sources (e.g., pollution and greenhouse gases), and the whole atmosphere composition. Important science questions include, but are not limited to:

- How are global air quality and climate being affected by long-range transportation of pollution plumes (e.g., aerosols, CO, NO_2, etc.)?
- What are the processes that determine the composition of the Earth's whole atmosphere including the connections to solar activity?
- How does polar O_3 vary on shorter time scale?

<u>Cross-Cutting Opportunity (w/ Heliophysics):</u> The potential for simultaneous measurements of the Sun and Earth from the Moon is another example of a set of observations that would allow a better understanding of the processes and interactions that determine the composition of the Earth's whole atmosphere and its connection to solar activity. Such measurements would provide real-time space weather data for predictive modeling of the space environment. The focus of the observations would be global scale and long time scale measurements.

> ***Time Phasing:***
> **Middle:** most of these observations are well-defined in the current decadal survey and will be measured in detail with LEO/GEO satellites. With current technology

and the desired resolution, an instrument would require a moderate size telescope (~50cm), a suitable Earth viewing location, and necessary communication bandwidth to Earth.

Science Priority: High

Rationale: This Investigation will make important observations with direct societal impact (e.g., pollution and greenhouse gases). Data will compliment possible future LEO/GEO sensors. Lunar platform will enable a larger Earth viewing area as well as near continuous observations.

Investigation C: Detect Changes in the Earth's Albedo Variability

Top of atmosphere, full-hemisphere observations may significantly improve our understanding of the role of clouds in modifying the amount of solar radiation reaching the Earth's surface. The largest uncertainty in global climate sensitivity over the next century is cloud feedback. To constrain cloud feedback to 50%, a stability of 0.3 W/m^2 per decade is required (0.001/decade in global albedo). This level of accuracy may not be achievable using lunar-based instruments due to longer repeat time to see the same point on Earth, the variability of clouds, and the phase angle between the Earth and the Moon. However, the tracking of clouds over the southern oceans may improve the determination of wind fields (important for global atmospheric circulation models), and the monitoring of polar ice will be possible from the Moon. The Earth's global reflectance is the least well studied for its impact on global climate change. Earthshine observations would provide the most thorough and complete measurements of the Earth's reflectance and its seasonal changes, as well as its longer term evolution.

Time Phasing:

Early → Late: instrumentation to measure Earthshine could be small and tested almost immediately. However, more sophisticated instrumentation with larger (~1m) telescopes and tracking capability would require longer time horizons.

Science Priority: Low

Rationale: There is still a vigorous debate as to whether measurements of Earthshine from the lunar surface can provide the needed degree of accuracy for long-term albedo characterization. Specific areas of concern include: angular sampling (restricted by Sun-Earth-Moon geometry); spatial sampling (require global coverage); temporal sampling (restricting Earthshine to a certain lunar phase angle range and therefore, cannot achieve daily coverage). The Earthshine approach is unlikely to achieve the stability requirement needed for climate science. However, imaging of the global cloud/ice cover from lunar surface is easily achievable and could provide a relative/contextual framework for data acquired from LEO/GEO.

Investigation D: Monitor the Earth's Land/Ocean Surface

Land and ocean imaging could be enhanced by multi-angle remote sensing from the Moon, which is now only possible with LEO instruments (e.g. MISR). The time-variable changing incidence and emergence angles could allow the retrieval of certain properties such as ecosystem structure, and would more completely sample the BRDF for science applications (e.g., near 0 phase angle). The variable lighting geometry enabled by the fixed observation point from the Moon would enhance regional studies of vegetation phenology (timing and magnitude of ecosystem processes indicated by greenness measured as a function of time). Land surface monitoring/mapping could benefit from long-term measurements and compliment LEO and GEO observations. Polar studies would also be enhanced by lunar observations because of the paucity of sea-ice observations over the open ocean. The near-shore distribution of ice in the Arctic Ocean by LEO-based microwave satellites may be improved due to the improved spatial resolution from the Moon.

Time Phasing:
Early → Late: instrumentation to measure multi- to hyperspectral reflectance could be small and tested almost immediately. However, more sophisticated instrumentation with larger telescopes and tracking ability would require longer time horizons.

Science Priority: Medium

Rationale: This Investigation will make important observations with direct societal impact (e.g., land surface/vegetation change, ecosystem/ocean health, etc.). Data will compliment data from future LEO/GEO sensors. Lunar platform will enable a larger Earth viewing area as well as near continuous observations at different phase angles. Could be combined with other ES decadal survey investigations.

<u>Investigation E:</u> Detect and Examine Infrared Emission of the Earth

One of the most compelling observations of the Earth from the Moon would be in the thermal infrared (TIR) region. The Earth's relatively clear TIR atmospheric windows correspond to the wavelength region (8-12 microns) of maximum emitted surface energy for the global average temperature, and the region (3-5 microns) of maximum pixel-integrated temperature of volcanoes/fires. Furthermore, a majority of Earth-forming minerals and SO_2 plumes have diagnostic emissivity spectra in the 8-12 micron region, making TIR excellent for the study of surface composition. The detection and analysis of volcanic flows, eruption plumes, the distribution of forest fires, temporal changes in the temperature of cities (urban heat islands), precursors to large earthquakes, as well as sea surface temperature could all be accomplished. The potential science return and scalability of the instrumentation rank this investigation very high.

Time Phasing:
Early → Late: evolution of the instrument could be tiered from short to longer time scales. A design and implementation of instrumentation that would evolve from the simple/low cost to the more complex would be the preferred pathway in order to return data as quickly as possible. For example:

1. The deployment of a radiometer that could provide whole-Earth broadband temperature monitoring on the time scale of seconds.
2. The later addition of foreoptics and scanning for progressively better spatial resolution.
3. The final addition of a high resolution spectrometer for multispectral capabilities. Data from such a sensor could be automatically scanned for thermal anomalies and linked into a sensor network with instruments in GEO or LEO orbits for better feature discrimination on the surface. Such a sensor could be ideal for hazard monitoring of

fires (location, progression, biomass burning) and volcanoes (new detection, eruption progression, plume tracking).

Science Priority: High

Rationale: This Investigation will make important observations with direct societal impact (e.g., hazard monitoring, sea surface temperature, storm severity, heat waves, etc.). Data will compliment future LEO sensors. Lunar platform will enable a larger Earth viewing area than LEO/GEO as well as provide near continuous observations at different local solar times, which are critical for thermophysical measurements (e.g., thermal inertia, soil moisture).

<u>Investigation F:</u> Develop Radar Interferometry of Earth from the Moon

This investigation will require the largest investment in infrastructure, power, and site location. The instrument(s) could be used to determine the velocity fields on the Earth (e.g., open ocean surface currents) and provide a new data set that cannot be obtained from LEO or GEO orbits. Other interferometry investigations may also be productive, such as the topographic mapping of high latitude regions inaccessible to the Shuttle Radar Topographic Mapping (SRTM) mission, or the detection of ground deformation prior to large earthquakes/volcanic eruptions. Such observations might be complimentary to investigations that use LEO-based InSAR data. High-temporal radar backscatter imaging of the Earth, achieved during the collection of the interferometric data, would also enable refinement in the knowledge of sea-ice coverage, the structure of vegetation canopies, and the spatial/temporal distribution of areas of regional flooding.

<u>Infrastructure/Site Location Prerequisites:</u>

- Most desirable would be a near-side equatorial location.
- Specifics need to be resolved on how these studies might compliment observations obtained from LEO satellites (especially in a near-real time detection network).
- Significant mass and power (~ 50 kW) requirements.
- Two operational modes.
    1. Bistatic operation:
        - Requires multiple antennas and a transmitter to form a microwave interferometric array with a long baseline and extreme stability.
    2. Multi-static operation:
        - Requires a single transmitter on the Moon with continuous illumination of the Earth plus the use of future LEO satellites/airborne sensors as antennas.
        - Range to receiver is much reduced (much finer resolution can be achieved) using the same amount of transmit power (lower integration time).

<u>Issues/Trades:</u>

- Location and power source studies are critical.
- Download mass.
- Bi-static versus multi-static?

Time Phasing:

Late: will require significant infrastructure development on the Moon, large power source (~50 kW), site development, sortie capability, and large (35m) antennas (collapsible to ~2.5m x 0.5m for transport), which would produce 100m azimuthal resolution data.

Science Priority: High

Rationale: This system could provide data for a wide array of applications including all weather capability topographic mapping, tomography to produce full 3D imaging (e.g. of forest layers), sea ice coverage, etc. The data from such a system would compliment the most number of proposed ES decadal survey missions.

Investigation G: E/PO Opportunities Enabled by a Lunar-Based Earth Observatory (LBEO)

This new investigation was added because of its relative simplicity in implementation, its integration with the other proposed investigations, and the potential commercial onramps. The psychological impact of seeing Earth from space should not be underestimated. Images from the Apollo and Galileo missions have provided a global view of our home planet not available from LEO/GEO. Future observations must expand beyond the occasional photograph of the Earth to a more systematic and synoptic set of images/measurements that can only be realized and enabled by the lunar architecture. It would be a serious flaw if an outpost location were chosen with little to no opportunity to perform Earth observations, which can then be used for inspiring the public and improving science education.

Infrastructure/Site Location Prerequisites:

- A suitable surface location must be identified that provides desirable Earth viewing (> 90% of the time) and allows future servicing/repairs/upgrades during human or robotic sorties. Most desirable would be a near-side equatorial location.
- These images/data could be initially gathered from simple instruments easily deployed and in time, derived from other science instruments.

Time Phasing:
Early → Late: immediate Earth observations could be started on the first landed mission and continue with more complex infrastructure on the surface.

Science Priority: High

Rationale: the data from this investigation will provide critical outreach for the lunar program and connect it back to the public as well as to global climate changes. This integrates well with the proposed investigations. Three primary E/PO themes have emerged that would make use of these images/data:

1. *The "Blue Planet Webcam":* in the process of collecting visible and infrared spectroscopic data for other proposed science investigations, regular visible images of the Earth would be generated. These real-time whole Earth views to be an amazing educational resource that could be visualized in a "Google Earth" type online environment. This is also a potential commercial onramp.
2. *The Pulse of Planet Earth:* Monitoring the Earth and acquiring critically-needed measurements from which to model trends in the atmosphere, lithosphere, cryosphere, hydrosphere, and biosphere will be critical to future sustainability and

climate change. Tracking climate variability, air pollution sources and transport, natural hazards (e.g., extreme weather, volcanic plumes, hurricanes, lightning, etc.), seasonal and secular variations in polar ice, and vegetation health (e.g., spring greening) are all possible. Such data would be important for public consumption and useful for NASA.

3. *Building the "Earth Observatory":* if an actual observatory is built on the lunar surface to observe Earth, the underlying concept of an "observatory on a hill" would be very compelling to both global monitoring and exploration. This iconic view of what an observatory is on Earth (e.g., the telescope under the white dome on the mountain) would be duplicated on the Moon and the data collected would be used for the long-term health of the planet.

Investigation H: Lunar-Based Earth Observatory Demonstration

This new investigation was added because of both the critical need to identify an optimal Earth observing site (for all the other investigations) as well as the priority of the Administration for advancement of Earth Science. Under the Technology section of the Office of Science and Technology Policy (OSTP) website, it states, *"to strengthen NASA's missions in space science, weather, climate research, and aeronautical research"*. An excellent way of synoptic monitoring the Earth's climate and weather is to demonstrate the optimal site, technology, and instrument package needed for the future Lunar-Based Earth Observatory (LBEO). In addition to the complete characterization of the optimal site location, an initial instrument package containing a UV-VIS-TIR whole-disk imager would be deployed. The data could be used as a demonstration and future baseline for measurements of albedo, climate, atmospheric chemistry, surface/ocean temperature, clouds, etc. The data would begin to address investigations: A, B, C, D, E, and G.

Infrastructure/Site Location Prerequisites:

- Development of the ideal instrument suite (could be one *über* instrument or several smaller instruments with upgradable capabilities).
- Package should be expandable with time and the infrastructure should be modular in order to grow into the permanent Earth Observatory.
- Should be initially deployable from early robotic missions and accessible later by humans or robotic sorties.

Time Phasing:
Immediate (robotic) → Early: immediate Earth observations should be started within the first series of landed missions.

Science Priority: High

Rationale: the data and infrastructure from this investigation will provide a critical baseline for Earth Science and a platform for future instrument testing, upgrades, and new additions.

Goal Sci-D: Use the unique lunar environment as research tool

The Moon has a unique combination of environmental characteristics, establishing experimental boundary conditions, not collectively attainable on Earth that may be valuable and necessary to the investigation of High priority scientific questions. The following examples of lunar environmental characteristics should be considered illustrative and not exhaustive. For example, one significant and unique environmental characteristic is the long duration, steady 1/6 g_e environment present on 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. While the space radiation environment on the lunar surface is not unique (principally a combination of galactic cosmic rays, solar energetic particles, and commensurate neutron albedo), its combination with 1/6 g_e is. 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. Therefore, the possibilities exist for unique experiments/investigations to be performed at the proposed outpost.

Combustion Research

Preamble: Fundamental combustion-convection issues have direct bearing on practical problems of fire safety and control in this unique environment. Flames behave differently in zero gravity, earth gravity, and in low-gravity jitter that occurs in flight tests and on space platforms.

Objective Sci-D-1: Investigate and characterize the fundamental interactions of combustion and buoyant convection in lunar gravity.

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.

Prerequisites: Experimental facility with required space and diagnostic tools. The Fluids and Combustion facility aboard the ISS will provide the microgravity endpoint to supplement these investigations.

Time Phasing and Prioritization are the same for each Investigation.

Time Phasing:
Middle → Late: Results of this investigation are important for feed-forward application, but not time-critical.

Science Priority: Medium.

Rationale:

<u>Investigation A</u>: Investigate flame structure and instabilities near combustion limits, as defined by dilution, stoichiometry, temperature (low-temperature flames), etc.

<u>Investigation B</u>: 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.

<u>Investigation C</u>: **Examine relatively large, lean weakly buoyant flames in hydrogen and methane in lunar gravity.**

<u>Preamble</u>: These are our fiducial points for comparing to other more complex systems, and the building blocks for understanding more complex processes.

<u>Investigation D</u>: 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.

<u>Objective Sci-D-2</u>: Perform tests to understand and possibly discover new regimes of combustion.

New regimes of combustion have been demonstrated in microgravity conditions. In fact, a large, lean methane flame has been shown to be an analogue for the kind of weak ignition that could occur at the core of type Ia supernovae.

This phase of the research is exploratory, which, in the case of combustion, always produces surprises. This objective 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 objective are of fundamental interest that may be employed to refine combustion processes in general.

<u>Prerequisites</u>: Experimental facility with required space and diagnostic tools. The Fluids and Combustion facility aboard the ISS will provide the microgravity endpoint to supplement these investigations.

Time Phasing and Prioritization are the same for each Investigation.

Time Phasing:
<u>Middle → Late</u>: Results of this investigation are important for feed-forward application, but not time-critical.

Science Priority: Medium.

> ***Rationale***:

Investigation A: **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.**

Questions to be addressed by this Investigation are when do these structures exist in low gravity, and how do they change flammability limits?

Investigation B: **Investigate rarefied gas combustion, either as premixed flames or diffusion flames.**

Questions to be addressed by this Investigation are: Can chemical reaction waves propagate at low gravity and in rarefied conditions? How low can the pressure be?

Investigation C: **How does a large premixed reactive mixture, or a large flame, behave when exiting to a vacuum or to very low atmospheric pressure?**

Objective Sci-D-3: Investigate interactions of multiphase combustion processes and convection at lunar gravity.

Preamble: This objective 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.

Prerequisites: Experimental facility with required space and diagnostic tools. The Fluids and Combustion facility aboard the ISS will provide the microgravity endpoint to supplement these investigations.

Time Phasing and Prioritization are the same for each Investigation.

> ***Time Phasing***:
> **Early:** Results of this investigation impact fire safety.
>
> ***Science Priority***: High.
>
> ***Rationale***: Results of these Investigations impact fire safety.

Investigation A: Investigate the interaction of water mist with diffusion flames in lunar gravity.

Investigation B: Investigate the process of soot formation in lunar gravity.

Questions to be addressed by this Investigation are: Is soot formation different from 1-g? 0-g? How does the variation of *g* affect the timing and processes of soot formation?

<u>Investigation C</u>: Investigate the process of flame initiation and growth.

Questions to be addressed by this Investigation are: How is smoldering affected by low-g? How is flame spread over thick solid fuels affected?

<u>Objective Sci-D-4</u>: 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 these types of experiments.

<u>Prerequisites</u>: Multiple-site-emplacement capability and support structure.

Time Phasing and Prioritization are the same for each Investigation.

Time Phasing:
<u>Time Insensitive</u>

Science Priority: Low.

Rationale: Results of these Investigations are of intrinsic scientific interest.

<u>Investigation A</u>: Search for gravitational radiation using lunar-based, large-scale optical interferometry systems that take advantage of seismic stability of lunar surface.

<u>Investigation B</u>: Realize massive improvement in tests of general relativity (i.e. tests of equivalence principle) by placing *active* responder systems for lunar ranging.

<u>Investigation C</u>: 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.

<u>Investigation D</u>: 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).

Fluid Physics and Heat Transfer Research

Preamble: Fluid physics and heat transfer research in a lunar environment should focus on quantifying the impact of a sustained reduced-gravity level on flows and phenomena for which buoyancy plays a substantial role. The quantification of the effect of intermediate gravity on such phenomena will bridge the gap between Earth and microgravity results and point the way to the development of systems enabling efficient and robust human and robotic exploration of other heavenly bodies.

Buoyancy plays a role in several processes important to space exploration, including combustion, boiling and bubbly flows. Reduced gravity will also impact complex-fluid processes such as granular flows and fluidized beds, of potential importance to *in situ* resource utilization.

Objective Sci-D-5: Obtain experimental data to anchor multiphase flow models in partial gravity environment.

The lunar platform allows long-term access to 1/6 g_e 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 Martian exploration.

Prerequisites: Experimental facility and support equipment. The Fluids and Combustion facility aboard the ISS will provide the microgravity endpoint to supplement these investigations. There is the possibility that preliminary investigations may be conducted robotically.

Time Phasing and Prioritization are the same for each Investigation.

Time Phasing:
Early:

Science Priority: High

Rationale: Results of these Investigations impact liquid transport in life-science and propellant applications, ISRU applications, and heat transfer in habitat, pressurized surface transportation and surface suits.

Investigation A: Test simple two-phase flow through straight channels at different inclinations under partial gravity.

Investigation B: Test two-phase flow through porous media/packed beds under partial gravity.

Investigation C: Assess efficacy of boiling heat transfer under lunar gravity.

Objective Sci-D-6: 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 Martian exploration.

Prerequisites: Experimental facility and support equipment. The Fluids and Combustion facility aboard the ISS will provide the microgravity endpoint to supplement these investigations.

Time Phasing and Prioritization are the same for each Investigation.

Time Phasing:
Middle:

Science Priority: Medium

Rationale: Results could lead to more mass-efficient transport schemes for liquids in low and partial gravity.

Investigation A: Study low-Reynolds-number dynamic wetting in the presence of temperature gradients typical of the lunar environment and lunar gravity.

Investigation B: Validate relative importance of capillary-driven versus buoyancy-driven flow in various geometries.

Investigation C: Study the behavior of liquid wicking under lunar gravity.

Objective Sci-D-7: 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.

Prerequisites: Experimental facility and support equipment. There is the possibility that some of the preliminary investigations may be conducted robotically.

Time Phasing and Prioritization are the same for each Investigation.

Time Phasing:
Early:

Science Priority: High

Rationale: Results impact ISRU as well as site modification for infrastructure development, and the impact of dust accumulation without mitigation over long exposure times is unknown.

<u>Investigation A</u>: Obtain experimental data on gravity-driven, dense granular flows, such as flows out of a bin, corresponding to Earth-based design methods.

<u>Investigation B</u>: Investigate impact of accumulated lunar dust on exposed radiative, habitat, transportation, suit and optical surfaces.

<u>Investigation C</u>: 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.

<u>Justification</u>: Current studies utilize material that has been on Earth for upwards of 40 years. Additional understanding of the material is required to assess its toxicity in situ prior to returning humans to the Moon. Suggest adding that a larger quantity of lunar dust samples will be needed that is currently available from the Apollo missions. Also samples from different areas of the moon may be needed to verify if there are location differences.

<u>Objective Sci-D-8</u>: Investigate precipitation behavior in supercritical water in partial gravity environment.

Supercritical water applications are becoming more widespread in industry. The presence of the secondary phases shifts the critical point, impacting performance. Understanding critical-point shift under lunar gravity will yield greater understanding applicable to 1-g and reduced-g applications.

<u>Prerequisites</u>: Experimental facility and support equipment.

Time Phasing and Prioritization are the same for each Investigation.

Time Phasing:
<u>Time Insensitive</u>:

Science Priority: Low

Rationale: Results are of intrinsic scientific interest.

<u>Investigation A</u>: Measure salt deposition rate on heated surface in supercritcal water-salt solutions with and without flow.

<u>Investigation B</u>: Assess effects of Lewis number on homogeneous and heterogeneous salt precipitation in supercritical water-salt solutions.

Materials Processing Research

Preamble: The generation of oxygen from the lunar regolith involves materials-processing techniques that are gravity dependent. The investigation of candidate methods on the lunar surface will permit the refinement of theoretical models as well as validating similarity hypotheses necessary to implement scale-up.

Manufacturing processes such as liquid-phase sintering are dependent on gravity level, with significant differences noted between g_e and microgravity. The availability of long-duration exposure to lunar gravity will permit the refinement of theoretical/numerical models, leading to identification of the proper conditions to be employed for its use in manufacturing on the lunar surface, and, ultimately, to its use on Mars.

Objective Sci-D-9: 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 under short-duration (parabolic flight) exposure to 1/6 g_e need confirmation.

Prerequisites: Experimental facility and support equipment.

Time Phasing and Prioritization are the same for each Investigation.

Time Phasing:
Early: It is important to understand the ISRU potential early in the next era of lunar exploration to pave the way for permanent settlements.

Science Priority: High

Rationale: Investigations are into processes that provide mechanisms for oxygen production.

Investigation A: Study separation behavior within melt of solids and bubbles during oxygen production using electrolysis.

Investigation B: Investigate multiphase heat-transfer schemes required for oxygen production employing regolith reduction.

Objective Sci-D-10: Investigate the behavior of liquid-phase sintering under lunar gravity.

Liquid-phase sintering processes are gravity-dependent due to the fact that 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 Martian exploration.

Prerequisites: Experimental facility and support equipment.

Investigation A: Study the effect of solid volume fraction and varying operating conditions on liquid-phase sintering carried out on the lunar surface.

> ***Time Phasing***:
> **Middle**: Mid-term knowledge acquisition needed for long-term application.
>
> ***Science Priority***: Medium
>
> ***Rationale***:

Objective Sci-D-11: Study and assess effects on materials of long-duration exposure to the lunar environment.

Four-decade recorded history of exposure of materials to the lunar environment.

Prerequisites: Results of LDEF.

Time Phasing and Prioritization are the same for each Investigation.

> ***Time Phasing***:
> **Early**: Knowledge of long-duration effects is critical to design criteria for performance evaluation of future-landed systems.
>
> ***Science Priority***: High
>
> ***Rationale***: Provides ability to investigate effects on materials complementary to those employed in the Apollo era.

Investigation A: Analysis of human-emplaced materials from the Apollo era.

Investigation B: Early robotic placement of controlled material samples for evaluation in the lunar environment.

Life Sciences Research

Preamble: The ability of terrestrial life to adapt to a long-duration, fractional-gravity environment is clearly important to manned Space exploration, whether it be on the Moon with 1/6 g_e or Mars with 3/8 g_e. Data from experience in microgravity environments indicate changes ranging from the morphological structure of yeast to bone loss in humans. The lunar surface provides a gravitational environment that is within one order of magnitude of Earth's gravity, a range over which most biological responses exhibit their greatest variation to other independent variables.

Life sciences research on the lunar surface must therefore focus on the study of variable gravity levels on living systems and other environmental influences, to include exposure to radiation and dust. These environmental influences may be synergistic in their negative impacts on living systems. The results of research will not only impact crew health and safety, but yield results that can enhance our understanding of fundamental biological processes.

Objective Sci-D-12: Study effect on microbes of long-duration exposure to the lunar environment.

Microbial research is fundamental to both humans and plants and enables multigenerational studies that may be performed within limited time periods.

Prerequisites: None, in some cases; a centrifuge for sample preparation and variable gravity in others.

Investigation A: Study the effects of the lunar radiation environment and variable gravity on microbes.

Time Phasing:
Early:

Science Priority: Medium-High

Rationale: Microbes are historically sentinel organisms to understanding environmental impacts.

Investigation B: Study the effect of regolith on microbial systems with respect to toxicity and nutrient availability.

Time Phasing:
Early:

Science Priority: Medium

Rationale: Enables estimate of ISRU potential for the regolith in a lunar setting.

<u>Investigation C</u>: Assess metabolic changes affecting bioprocessing potential, virulence, and sensitivity to anti-microbials.

> ***Time Phasing***:
> **<u>Middle</u>**:
>
> ***Science Priority***: Medium-High
>
> ***Rationale***: Recent research from microgravity indicates significant increases in virulence and changes that can affect microbial population dynamics.

<u>Objective Sci-D-13</u>: Assess effect on plants of long-duration exposure to the lunar environment.

Plant research on the lunar surface is fundamental to ISRU and sustained human habitats.

<u>Prerequisites</u>: None, in some cases; a small centrifuge for variable gravity in others.

<u>Investigation A</u>: Study the effects of the lunar radiation environment and variable gravity on plants.

> ***Time Phasing***:
> **<u>Middle → Late</u>**:
>
> ***Science Priority***: Medium → High
>
> ***Rationale***: In addition to providing a sustained food source, plants provide a test bed for studying the effects of the lunar environment on higher-level organisms.

<u>Investigation B</u>: Study the use of regolith as a growth medium for plants.

> ***Time Phasing***:
> **<u>Middle</u>**:
>
> ***Science Priority***: Medium → High
>
> ***Rationale***: Assessment of ISRU potential for the regolith in a lunar setting.

<u>Objective Sci-D-14</u>: 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 depends.

Keeping humans healthy and at peak performance during extended stays on the Moon will require an understanding of how features of the lunar environment (none of which can be simulated on Earth) can affect human health.

<u>Prerequisites</u>: Sustained human presence on the moon for Investigation B.

<u>Investigation A</u>: Conduct fundamental research to understand the physiological and biological effects of the lunar environment on non-human life forms.

> ***Time Phasing***:
> **<u>Early</u>**: Provides feed-forward information for Investigation B.
>
> ***Science Priority***: High
>
> ***Rationale***: Crew health and safety, in accordance with priorities and implementation of NASA's Human Research Program.

<u>Investigation B</u>: Conduct fundamental research to understand the physiological, biological, and mental effects of the lunar environment on humans.

<u>Preamble</u>: This Investigation will measure the cumulative effects of fractional gravity, radiation and dust on biological systems.

> ***Time Phasing***:
> **<u>Middle → Late</u>**:
>
> ***Science Priority***: High
>
> ***Rationale***: Crew health and safety, in accordance with priorities and implementation of NASA's Human Research Program.

<u>Objective Sci-D-15</u>: Study the key physiological effects of the combined lunar environment on living systems and the effect of pharmacological and other countermeasures.

Understanding the physiological and biological effects (such as bone and muscle loss, diminished immune efficiency, slower wound healing, human nutrition needs, and poorer cognitive performance, in addition to pointing out unanticipated effects of the exploration environment) can be used to design mitigation strategies for extended stays and predict responses to the Martian environment.

Prerequisites: Sustained human presence on the moon for Investigation B.

Investigation A: Evaluate the impact of the combined lunar environment with and without the use of countermeasures on cellular oxidative damage.

> ***Time Phasing***:
> **Early**: Provides feed-forward information for Investigation B.
>
> ***Science Priority***: High
>
> ***Rationale***:

Investigation B: Evaluate the impact of the combined lunar environment with and without the use of countermeasures on musculoskeletal system.

> ***Time Phasing***:
> **Middle → Late**:
>
> ***Science Priority***: High
>
> ***Rationale***: Crew health and safety, in accordance with priorities and implementation of NASA's Human Research Program.

Investigation C: Evaluate the efficacy of pharmacological countermeasures employed under variable radiation and gravity environments.

> ***Time Phasing***:
> **Middle → Late**:
>
> ***Science Priority***: High
>
> ***Rationale***: Crew health and safety, in accordance with priorities and implementation of NASA's Human Research Program.

<u>Objective Sci-D-16</u>: Evaluate consequences of long-duration exposure to lunar gravity on the human musculo-skeletal system.

Experiences with muscle atrophy and bone loss due to prolonged exposure to microgravity have necessitated the development of counter-measures to ensure crew health. What is the rate at which these conditions progress in 1/6 g? Are countermeasures still necessary; which countermeasures and how much exercise time is required?

<u>Prerequisites</u>: Long-term presence of crew on the lunar surface.

Time Phasing and Prioritization are the same for each Investigation.

Time Phasing:
Middle → Late: Infrastructure is needed to conduct the Investigations under this Objective.

Priority: High

Rationale: Crew health and safety, in accordance with priorities and implementation of NASA's Human Research Program.

<u>Investigation A</u>: Determine if the lunar radiation environment alters the processes of reproduction, development, DNA damage and repair, metabolism, behavior, and aging.

<u>Investigation B</u>: 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.

<u>Investigation C</u>: Evaluate the use of radiation sensors and shielding materials using non-human biological systems.

<u>Investigation D</u>: Evaluate multigenerational studies with simple multicellular and unicellular organisms to understand long term effects and adaptation to the lunar radiation environment.

<u>Investigation E</u>: Understand the biological effects of lunar dust on model specimens/systems and interactions with the radiation environment.

<u>Objective Sci-D-17</u>: Study the effects of lunar radiation on biological model systems.

We must understand the impact of space missions beyond low Earth orbits on crew health, including prolonged exposures to cosmic radiation, and then identify and develop specific countermeasure strategies to reduce or even eliminate verse consequences, to ensure crew health and performance.

<u>Prerequisites</u>: Experimental facility and support equipment

Time Phasing and Prioritization are the same for each Investigation.

> ***Time Phasing***:
> **Middle → Late:** Infrastructure is needed to conduct the Investigations under this Objective.
>
> ***Priority***: High
>
> ***Rationale***: Crew health and safety, in accordance with priorities and implementation of NASA's Human Research Program. Important to determine 1/6 g and radiation affects on humans for long-term stays and for feed-forward implications. Can only be started during the middle stage of lunar exploration.

<u>Investigation A</u>: Determine if the lunar radiation environment alters the processes of reproduction, development, DNA damage and repair, metabolism, behavior, and aging.

<u>Investigation B</u>: 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.

<u>Investigation C</u>: 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.

<u>Investigation D</u>: Evaluate multigenerational studies with simple multicellular and unicellular organisms to understand long term effects and adaptation.

<u>Investigation E</u>: Understand the biological effects of lunar dust on model specimens/systems and interactions with the radiation environment.

Objective Sci-D-18: 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.

Time Phasing and Prioritization are the same for each Investigation.

> ***Time Phasing***:
> **Middle → Late:** Infrastructure is needed to conduct the Investigations under this Objective.
>
> ***Priority***: High
>
> ***Rationale***: Crew health and safety, in accordance with priorities and implementation of NASA's Human Research Program.

Investigation A: Investigate changes in the physiological microflora using animal model specimens.

Investigation B: Investigate changes in immune system function using animal model specimens.

Investigation C: 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.

Investigation D: Investigate changes in microbial virulence due to changes in gravity conditions. The study includes multicellular and unicelluar microbes and viruses.

Investigation E: Investigate changes to normal biological functions at the physiological, cellular, biochemical, and molecular levels using a diverse array of biological model specimens.

Objective Sci-D-19: Understand the effects/interactions of lunar gravity and the transitions between lunar gravity, microgravity; and Earth-normal gravity on reproduction and development, genetic stability, and aging.

The use of model organisms in the lunar environment (even in controlled habitats) will be invaluable for understanding long-term adaptive responses of Earth-based living organisms to environmental parameters of the lunar surface such as fractional gravity.

Time Phasing and Prioritization are the same for each Investigation.

Time Phasing:
Middle → Late: Infrastructure is needed to conduct the Investigations under this Objective.

Priority: High

Rationale: Crew health and safety, in accordance with priorities and implementation of NASA's Human Research Program.

Investigation A: Evaluate long-term effects and adaptation to the lunar gravitational environment of model specimens. Emphasis on in-situ analysis.

Investigation B: 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).

Objective Sci-D-20: 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.

Time Phasing:
Middle → Late: Infrastructure is needed to conduct the Investigations under this Objective.

Priority: High

Rationale: Crew health and safety, in accordance with priorities and implementation of NASA's Human Research Program.

Investigation A: Evaluate the effects of lunar gravity on g-sensing, signal transduction, and growth response in a variety of model plants.

Objective Sci-D-21: Evaluate the use and effectiveness of model plants in ecological life support systems.

Our knowledge of mutations in rapidly proliferating populations (esp. microbial) during long duration stays on the lunar surface is lacking. The studies can increase our knowledge of risks to human health and concomitantly increases our capability to manage, mitigate, or eliminate microbial risks to human health. Improved understanding of accelerated microbe mutation and virulence may help in the development of anti-microbial therapies for evolving terrestrial microbes. Understanding changes in floral nutrient content under environmental stressors is important for in situ food production.

Prerequisites: Long-term presence of crew on lunar surface

Time Phasing and Prioritization are the same for each Investigation.

Time Phasing:
Middle → Late: Infrastructure is needed to conduct the Investigations under this Objective.

Priority: High

Rationale: Crew health and safety, in accordance with priorities and implementation of NASA's Human Research Program.

Investigation A: 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).

Investigation B: 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)

Objective Sci-D-22: 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.

Prerequisites: Instrumentation for making and recording measurements.

Time Phasing and Prioritization are the same for each Investigation.

Time Phasing:
Early:

Science Priority: High

Rationale: The Investigations are needed for crew safety and mission success.

Investigation A: Establish a lunar environmental monitoring station to measure environmental variables such as temperature, vibration, dust collection, radiation, seismic activity, and gravity.

Investigation B: Provide real-time environmental information relevant to daily lunar operations.

Preamble: This Investigation will track the ability of the data to inform crews of potential hazards that can increase operational mission safety.

Feed Forward (FF) Theme: Use the Moon to Prepare for Future Missions to Mars and Other Destinations.

Purpose: Establish the Mars mission risk reduction technologies, systems and operational techniques that could be developed through a lunar exploration program – The following evaluation criteria will be used to evaluate candidate ideas:

- Mars/Small Body Risk Reduction Value: How well do the candidates address the key risk reduction areas identified through NASA's robotic and human Mars mission planning studies.
- Lunar Platform Value: Do candidates leverage the unique attributes of a lunar program to achieve success – or – would other platforms be more effective from a technical/cost perspective.

There are three Goals under this theme, the first two focused on Mars. One addresses hardware (Goal FF-A with 9 Objectives and 38 Investigations), the second operations (Goal FF-B with 3 Objectives and 13 Investigations), and the third is focused on using the Moon to prepare for future missions to small bodies.

Timing for individual investigations is driven by when the capability would be required for lunar applications since these technologies would be supporting lunar activities not done specifically as Mars technology demonstrations.

Goal FF-A: Identify and test technologies on the Moon to enable robotic and human solar system science and exploration.

The focus of Mars enabling technology research is on surface systems development. While the Moon and Mars have different gravities and drastically different environments (e.g., soil properties) both are still hostile environments that require similar functional capabilities for humans to explore and live off Earth. Conversely, for many Mars systems, the Earth can serve as a more cost effective analog for evaluating technologies, components, subsystems and integrated systems.

At the component and subsystem level, many Mars technologies have gravity dependent components that perform functions such as phase separation or 2-phase flow control. It is unclear whether the gravity field of the Moon or Earth is a better analog for evaluating these technologies. Preliminary research will be required at the flow-rates and capillary diameters that are being considered for component designs to evaluate the best testing ground for these components.

At the integrated system level, the risk reduction value of actually deploying Mars-prototype integrated systems on the Moon for evaluation may provide additional value that testing on Earth cannot. But, again, additional preliminary research should be done to see if the value associated with this approach outweighs the associated costs when compared against performing these integrated tests on Earth.

<u>Objective FF-A-1</u>: Develop surface life support systems to reduce risks associated with long duration Martian surface stay times.

<u>General Requirements:</u>

- Evaluate technologies required to achieve life support closure of >90% (TBD), which will be required to support Mars surface systems operations.
- Evaluate technologies required to reduce surface system life support IMLEO by 25% (TBD) and Total System Volume by 25% (TBD) over current ISS technologies.
- Evaluate technologies that reduce crew interaction requirements by 50% (TBD) over ISS baseline systems
- Evaluate life support technologies that leverage partial gravity environments to increase efficiencies and reduce IMLEO over ISS baseline systems.
- Evaluate life support technologies that leverage in-situ resources in areas that have applicability to Mars surface operations
- Perform extended operational evaluation of an integrated 90% (TBD) closure surface life support system to simulate Mars surface stay periods of >500 days

Variable gravity sensitivities resulted in medium ratings while areas which have never been tested in space as integrated systems were rated high. Areas where Earth based testing or previous space testing have been extensive were rated low.

<u>Investigation A</u>: Evaluate air revitalization technologies.

<u>Preamble</u>: This is required in areas such as carbon dioxide reduction to increase loop closure over ISS baseline and in areas such as trace contaminant control where reduction in IMLEO need to be increased over ISS baseline. Also, evaluate technologies where partial gravity environments can be leveraged to design systems with lower IMLEO requirements versus ISS baseline systems.

Time Phasing:
Middle → Late: Valuable data will be collected during extended surface stays.

Priority: Medium

Rationale: Earth and space based (ISS, Skylab, Mir, Salyut) research has been significant in advancing these technologies. Lunar evaluation will be valuable in areas where gravity sensitivities play a key role (e.g., water electrolysis).

<u>Investigation B</u>: Evaluate water management and recovery technologies.

<u>Preamble</u>: Technologies that reduce IMLEO requirements over the ISS baseline are critical for human missions to Mars. Also, evaluate technologies where partial gravity environments can be leveraged to design systems with lower IMLEO requirements versus ISS baseline systems.

Time Phasing:
Middle → Late: Valuable data will be collected during extended surface stays.

Priority: Medium

Rationale: Earth and space based (ISS, Skylab, Mir, Salyut) research has been significant in advancing these technologies. Lunar evaluation will be valuable in areas where gravity sensitivities play a key role (e.g., two-phase flow, two-phase separation).

Investigation C: Test waste management technologies.

Preamble: There is a critical need to recover resources from manufactured and packaging waste, as well as human waste, in order to converge upon a closed-loop life support system.

Time Phasing:
Middle → Late: Valuable data will be collected during extended surface stays.

Priority: Medium

Rationale: Earth based research can advance technologies to inform Mars mission designs. Lunar evaluation will be valuable in areas where gravity sensitivities play a key role (e.g., two-phase flow, two-phase separation).

Investigation D: Test bioregenerative technologies.

Preamble: This is needed to support wastewater processing, air revitalization and food production.

Time Phasing:
Middle → Late: Valuable data will be collected during extended surface stays.

Priority: High

Rationale: Almost all human architectures for Mars surface missions involve bioregenerative life support components. Since no testing of this type has been done on a planetary surface – lunar evaluation of this type of system could be critical for designing a system for Mars.

Investigation E: Perform long-duration testing of an integrated surface life support system.

Preamble: This is required to simulate Mars surface stay times exceeding 500 days.

Time Phasing:
Middle → Late: Valuable data will be collected during extended surface stays.

Science Priority: High

Rationale: All human architectures for Mars surface missions involve integrated life support systems. ISS provides a significant dataset on partial closed loop operations in microgravity. However, since no testing of this type has been done on a planetary surface in partial gravity – lunar evaluation of this type of system could be critical for validating a system for Mars.

Investigation F: Evaluate environmental monitoring technologies for gas and liquid consumables to ensure quality over long duration missions.

Preamble: This Investigation should specifically address technologies where partial gravity can be used to improve performance over the ISS baseline.

Time Phasing:
Middle → Late: Data can be collected during extended surface stays.

Priority: Low

Rationale: Earth and space based (ISS, Skylab, Mir, Salyut) research has been significant in advancing these technologies. While it is desirable to conduct such an investigation on the lunar surface, the need is not critical.

Investigation G: **Evaluate fire detection and suppression strategies for partial-g environments.**

Preamble: This Investigation specifically addresses technologies where partial gravity can be used to improve performance over the ISS baseline.

Time Phasing:
Middle → Late: Valuable data will be collected during extended surface stays.

Priority: Medium

Rationale: Earth and space based (ISS, Skylab, Mir, Salyut) research has been significant in advancing these technologies. Lunar evaluation will be valuable in areas where gravity sensitivities play a key role.

Objective FF-A-2: Develop Crew Health Systems That Enable Safe, Long Duration, Surface Stays.

Low-gravity, dust, radiation, and isolation will have combined or integrated effects on human biology at all levels and human psychology during long-duration exploration missions on planetary surfaces.

In some areas, Earth-based research is adequate for informing Mars mission decisions while in other cases gravity sensitivity, radiation or other environmental factors make the Moon a valuable testbed.

<u>Investigation A</u>: Test countermeasure technologies.

<u>Preamble</u>: The technologies need to be tested so as to assure human performance remains at an acceptable standard.

> ***Time Phasing***:
> **Middle → Late:** Valuable data will be collected during extended surface stays.
>
> ***Priority***: High
>
> ***Rationale***: Current research in microgravity countermeasures may not allow for extrapolation to partial gravity environments. Lunar research will be critical in establishing a partial gravity data point for Mars mission design. This research should be tied back to fundamental research on biological and physiological effects of partial lunar environment (e.g., partial gravity, oxygen concentration, reduced pressure) over long periods to inform countermeasure requirements.

<u>Investigation B</u>: Test medical diagnosis and treatment technologies.

<u>Preamble</u>: This investigation is required for medium to long stay to allow well-patient care in addition to the treatment of illnesses/injuries on a planetary surface (either the Moon or Mars or beyond).

> ***Time Phasing***:
> **Middle → Late:** Valuable data will be collected during extended surface stays.
>
> ***Priority***: Medium
>
> ***Rationale***: Telemedicine, minimally invasive techniques and remote health care are technology areas being matured on Earth. However, lunar research will provide information on healing and recovery from injuries in partial gravity.

<u>Investigation C</u>: Test long-term food storage technologies.

<u>Preamble</u>: This investigation is required to ensure lasting nutritional value of foods stored for extended periods of time on a planetary surface.

> ***Time Phasing***:
> **Middle → Late:** Data can be collected during extended surface stays.
>
> ***Priority***: Low
>
> ***Rationale***: Experience on Earth and in Space (ISS) has been significant. However – the lunar radiation environment effects on shelf life will inform operational protocols for both Mars transit and surface systems.

Investigation D: **Perform psychological health research on impact of extreme isolations for periods of >500 days.**

> ***Time Phasing***:
> **Middle → Late:** Data can be collected during extended surface stays.
>
> ***Priority***: Low
>
> ***Rationale***: Research on earth and space based (ISS, Skylab, Mir, Salyut) isolated environments has been significant.

Objective FF-A-3: Develop surface mobility capabilities that allow human crews to efficiently and safely explore the surface of Mars.

Extensive extravehicular activity (EVA) will be needed for crews to work on and explore planetary surfaces. Major surface features on the Moon and Mars, prime targets for intensive investigations, are on the order on many 10's to several 100's km apart, and capabilities beyond those used during Apollo will be needed to traverse these great distances.

Although advances in surface mobility will be required to support Mars missions – the role of lunar development/testing varies depending on the technology.

Investigation A: **Test surface mobility systems**.

Preamble: Surface mobility systems with the following attributes need to be tested:
RANGE: traverse distances of at least several 100s km away from a landing or outpost site,
DURATION: surface exploration sorties lasting up to several weeks
TERRAIN: Capability to access both steep (defined by slopes of >XX degree) and rough terrain
TIME: Use time on the surface as efficiently as possible, so as to maximize the fraction used for science exploration. Optimize Autonomy.

> ***Time Phasing***:
> **Middle:** This would "be" the lunar extended presence facility.
>
> ***Priority***: High
>
> ***Rationale***: Almost all human architectures for Mars surface missions involve long distance traverses for access to geological diversity. Since no testing of this type has been done on a planetary surface – lunar evaluation of this type of system could be critical for designing a system for Mars.

<u>Investigation B</u>: Test advanced space suit technologies.

<u>Preamble</u>: New space suit technologies must allow greater mobility, dexterity, and range than the space suits used during the Apollo, Space Shuttle, and International Space Station programs. In order to enhance surface operations on the Moon and Mars.

> ***Time Phasing***:
> **Early → Late:** Timing is driven by when the capability would be required for lunar applications since these technologies would be supporting lunar activities – not – done specifically as Mars technology demonstrations.
>
> ***Priority***: Medium
>
> ***Rationale***: Space suit technologies have been matured with past human space programs. However, lunar missions will add to this dataset so that this technology can be improved in an evolutionary manner. Differences in lunar and Martian environments drive toward different technology solutions.

<u>Investigation C:</u> Test robotic field assistant technologies.

<u>Preamble</u>: These are required to complement and augment the abilities of human crew members exploring or working on a planetary surface.

> ***Time Phasing***:
> **Middle → Late:** Continuing development of already mature technology. However, lunar missions will add to this dataset so that this technology can be improved in an evolutionary manner.
>
> ***Priority***: Low
>
> ***Rationale***: Investigations can rely on heritage systems (e.g., ISS, STS) or earth developed technologies (e.g., DoD) to provide Mars required capability.

<u>Objective FF-A-4</u>: Develop the capability to acquire and use local resources to sustain long-term exploration and habitation of planetary surfaces.

Mars possesses abundant natural resources that could be used to supply human consumables, such as air and water, and construction materials. Relying on earth-based supplies for extended operations on the Mars is likely neither affordable or sustainable, and achieving a certain level of self-sufficiency would also reduce the risks involved with the delivery of those supplies.

The Mars robotic program is and will continue to identify and characterize Mars resources. Differences in lunar and Martian environments drive toward different technology solutions for resource utilization. In a few cases (electrolysis and phase separation), gravity sensitivities will benefit from lunar testing.

Investigation A: Test resource identification/characterization procedures and technologies.

Time Phasing: **Not Applicable.**

Priority: Low

Rationale: The Mars robotic program is and will continue to identify and characterize Mars resources.

Investigation B: Test electrolysis technologies especially for water and carbon dioxide.

Time Phasing:
Middle → Late: Timing is driven by when the capability would be required for lunar applications since this technology would be supporting lunar activities – not – done specifically as Mars technology demonstrations.

Priority: Medium

Rationale: Electrolysis has applications to Mars ISRU (carbon dioxide). Due to gravity dependencies this technology would benefit from lunar evaluation.

Investigation C: Test technologies to produce water from frozen regoliths.

Time Phasing:
Middle → Late: Timing driven by lunar applications (only if a permanently shadowed polar location is selected for a robotic or human mission).

Priority: Low

Rationale: Current Mars architecture focuses on water production from atmospheric carbon dioxide electrolysis and hydrogen from Earth.

Investigation D: Test phase separation technologies for handling solids, liquids, and gases.

Time Phasing:
Middle → Late: Timing is driven by when the capability would be required for lunar applications since this technology would be supporting lunar activities – not – done specifically as Mars technology demonstrations.

Priority: Medium

Rationale: Due to gravity sensitivities lunar testing of these technologies would be important in providing information for Mars system designs.

Investigation E: Test product storage technologies.

Time Phasing: **Not Applicable**.

Priority: Low

Rationale: Differences in lunar and Martian environments drive toward different technology solutions.

Investigation F: Test technologies to produce construction materials or paved/prepared surfaces.

Time Phasing:
Late: Requires significant supporting infrastructure.

Priority: Low

Rationale: Current Mars Architecture designs look at autonomously deployed surface infrastructure for single ~500 day missions. Applications to produce construction materials on Mars would be for very long term Mars settlement concepts which are currently thought of as very far in the future.

Objective FF-A-5: Develop the capability to produce adequate levels of power on planetary surfaces to allow human crews to work and live productively.

Studies of initial planetary outposts have shown power levels in the several 10's of kW are needed on a continuous basis for sustained human operations. When resource development is considered in addition to the outposts, the power levels increase to many 10's of kW, and sometimes to a few 100's of kW. It is not practical to rely only on solar technologies for producing these high power level on the Mars surface.

Although advances in power generation and energy storage will be required to support Mars missions – the role of lunar development/testing varies depending on the technology.

Investigation A: Test surface fission power system technologies.

Preamble: Power systems need to be capable of generating >100kW. These systems should be capable of being autonomously deployed and able to initiate/sustain power generation without human interaction. Systems for providing radiation shielding to ensure crew safety should be incorporated in the design.

Time Phasing:
Late: This would "be" the lunar extended presence power system.

Priority: High

Rationale: Almost all human architectures for Mars surface missions involve surface fission power systems due to the high power levels required. Since no testing of this type has been done on a planetary surface – lunar evaluation of this type of system could be critical for designing systems for Mars transit (nuclear thermal rocket) and surface applications.

Investigation B: Test radioisotope thermal generator technologies for small remote science stations and observatories.

Preamble: These systems would need to supply power at the level of >1kW. These systems should be capable of being autonomously deployed and able to initiate/sustain power generation without human interaction. Systems for providing radiation shielding to ensure crew safety should be incorporated in the design.

Time Phasing:
Early → Late: Data can be collected during extended surface stays.

Priority: Medium

Rationale: Early lunar applications could involve fixed units associated with small remote science stations (e.g., geophysical stations) while long-term applications could involve evaluation of mobile systems.

Investigation C: Test rechargeable energy storage technologies for fixed and mobile surface applications.

Time Phasing:
Middle → Late: Technologies for lunar overnight stays and for mobile systems would add to the evolution of this technology.

Priority: Low

Rationale: Commercial drivers for these technologies can be leveraged for Mars mission application.

Objective FF-A-6: Develop the capability to autonomously land safely and accurately on Mars.

The surfaces of the Moon and Mars are unprepared surfaces with natural hazards such as boulders, craters, and sloping terrain. Mars landings through an atmosphere are much different than lunar landings – but – there are some technologies for landing guidance that could have similarities.

Mars robotic missions (e.g., MER, Phoenix, MSL) are the best targets of opportunity for technology evaluation. Lunar missions will add to this dataset so that this technology can be improved in an evolutionary manner.

Time Phasing and Prioritization are the same for each Investigation.

Time Phasing:
Early → Late: Lunar missions will add to the dataset from Mars landers so that this technology can be improved in an evolutionary manner.

Priority: Low

Rationale: Mars robotic missions (e.g., MER, Phoenix, MSL) are the best targets of opportunity for technology evaluation.

Investigation A: Test terrain-relative precision landing systems with targeting accuracy better than 100m (TBD).

Investigation B: Test hazard tolerant landing systems.

Investigation C: Test autonomous terminal hazard avoidance technologies, for those hazards that cannot be tolerated.

Objective FF-A-7: Develop the capability to provide or construct structures on planetary surfaces adequate for long-duration habitation by humans, and made of materials that will endure extended exposure to the deep-space environment.

Unlike the Apollo missions where the astronaut crew lived out of their lander vehicle, sustained presence on the Moon or Mars will require the use of pressurized habitats emplaced on the planetary surface. Sustained presence on the Moon or Mars will require structural materials that can retain their integrity for extended periods of time after continuous exposure to radiation, micrometeoroids, and extreme temperatures.

Since long duration surface habitation facilities have never been developed – it would be highly beneficial to reduce Mars mission risk by demonstrating these capabilities at the Moon prior to doing this at an extremely remote location. Specifically, Mars architectures typically rely on an autonomously deployed monolithic hab/lab facility.

Demonstration can begin with the first lunar delivered habitat for outpost operations but use of in-situ materials will require additional infrastructure.

<u>Investigation A</u>: Test monolithic habitat technologies on the lunar surface.

<u>Preamble</u>: These technologies should incorporate the capability for autonomous deployment and operations without human intervention. These technologies should provide the capability to be 100% ready for crew occupancy when the initial crew arrives at the surface.

> ***Time Phasing***:
> **Middle:** This would "be" the lunar extended presence facility.
>
> ***Priority***: High
>
> ***Rationale***: Almost all human architectures for Mars surface missions involve an autonomously deployed hab/lab facility. Since no testing of this type has been done on a planetary surface – lunar evaluation of this type of system could be critical for designing a system for Mars.

<u>Investigation B</u>: Test manufactured structures technologies that use construction materials made from natural lunar resources.

<u>Preamble</u>: This investigation includes an evaluation of technologies that can reduce IMLEO while minimizing the amount of crew involvement required to generate products from available resources.

> ***Time Phasing***:
> **Late:** Requires significant supporting infrastructure.
>
> ***Priority***: Low
>
> ***Rationale***: Current Mars Architecture designs look at autonomously deployed surface infrastructure for single ~500 day missions. Applications of manufactured structures on Mars would be for very long term Mars settlement concepts which are currently thought of as very far in the future.

<u>Objective FF-A-8</u>: Develop the capability for crews on Mars to communicate with other assets on the surface, and navigate to and from those assets.

Working and living on the Moon and Mars will involve traveling long distances, over the horizon from any established facility, and likely beyond line-of-sight of any fixed communication or navigation asset at that facility. Neither the Moon or Mars have a strong global magnetic field available for surface navigation.

Investigations can rely on heritage systems (e.g., time/clock) or earth developed technologies to provide Mars required capability.

Time Phasing and Prioritization are the same for each Investigation.

Time Phasing:
Not Applicable: Continuing development of already mature technology.

Priority: Low

Rationale: Investigations can rely on heritage systems (e.g., time/clock) or earth developed technologies to provide Mars required capability.

Investigation A: Test non-line-of-sight communications technologies on the lunar surface.

Investigation B: Test technologies for navigating on the lunar surface without a strong magnetic field.

Investigation C: Establish high bandwidth Earth-Moon communication links that could support public engagement activities.

Investigation D: Establish time and clock capabilities to assist vehicles in cis-lunar space and surface systems in determining their relative and absolute time.

Investigation E: Establish emergency position determination services to support Search and Rescue operations.

Objective FF-A-9: Develop the capability for human crews to operate safely on planetary surfaces, protected from the extreme environment and hazards.

Due to the lack of measurable magnetic fields and the existence of thin or very tenuous atmospheres, humans working and living on the Moon and Mars will be immersed in environments with higher levels of radiation and micrometeoroid impacts than on Earth. Other environmental hazards like dust and extreme temperatures will affect design of all planetary surface systems.

There are a number of high priority investigations where the Moon can play a key role in risk reduction. In a few areas, although not critical, data from the Moon could augment and add value.

Investigation A: Test radiation shielding technologies.

Preamble: This Investigation is essential for protecting astronauts on the lunar surface from galactic cosmic rays (GCR) and solar energetic particle (SEP) events.

> ***Time Phasing***:
> **Early:** Data points collected from the CEV, Altair and surface hab/lab facilities will all be valuable in establishing the optimal shielding for Mars transit/surface systems.
>
> ***Priority***: High
>
> ***Rationale***: ISS is within the Van Allen belts protecting the crews from most radiation – Moon will provide a unique testbed for human operations in a high radiation environment – applicable to both Mars transit and surface stays.

Investigation B: Test micrometeorite protection technologies to prevent damage caused by micrometeorite impacts.

Preamble: This Investigation will leverage ISS experience to determine if additional technological advances are required to support >500 day surface stays on Mars.

> ***Time Phasing***:
> **Early → Late:** Data can be collected during all lunar surface stays.
>
> ***Priority***: Low
>
> ***Rationale***: ISS and other orbiting assets have provided a good database of micrometeoroid and orbit debris impacts that can be used to establish Mars transit vehicle shielding requirements (Mars surface systems would be protected by the atmosphere). Lunar missions will add to this dataset.

Investigation C: Test dust mitigation technologies to prevent dust from interfering with mechanical systems and causing health problems for astronaut crews.

> ***Time Phasing***:
> **Early:** Mars system design impacts will require lunar data as soon as possible. In-situ analysis and returned samples of Mars dust would be needed as well to better understand the variations between the Moon and Mars.
>
> ***Priority***: High
>
> ***Rationale***: Although there are differences in composition and other characteristics between lunar and Martian dust – the moon will provide important data on how to design systems for a high dust environment.

<u>Investigation D</u>: Test forward and backward planetary protection technologies to prepare for human and robotic operations on Mars.

Time Phasing:
Early → Middle: Samples require protection from the onset – but preliminary examination protocols require additional infrastructure and human presence. Suits, habs, labs, etc. can be improved in an evolutionary manner.

Priority: High

Rationale: Earth based testing of a high fidelity system would greatly reduce risk – but lunar verification would be required to increase overall confidence level.

<u>Investigation E</u>: Establish space weather modeling, forecasting and monitoring capabilities.

<u>Preamble</u>: The capabilities established under this investigation can be used to warn Mars transit/surface crews of potentially hazardous solar events. The goal of these systems should be to provide as early a warning as possible of dangers.

Time Phasing:
Early → Late: Information is needed early in the Mars transit/surface vehicle design phase. Although there are many current sources of data (Earth orbiting satellites, Earth-Sun L1 satellites) data collected from lunar missions will add to this data set.

Priority: Low

Rationale: Does not rely on a lunar program as a key way of developing this capability to support Mars missions. Planning for Mars transit may actually provide information that could be used in lunar surface system designs since Mars transit has greater mass and duration requirements and lacks ISRU.

<u>Goal FF-B</u>: Use the Moon as a test-bed for missions operations and exploration techniques to reduce the risks and increase the productivity of future missions to Mars and beyond.

The nearness of the Moon with respect to Earth allows for opportunities in testing of surface mission operations and exploration techniques without the concern that help from Earth or the ability of the crew to return safely is more than a year away.

The Moon will serve as a training ground for mission operations that will enable sustained human exploration of Mars and beyond in terms of crew autonomy and human-robotic interaction.

<u>Objective FF-B-1</u>: Develop the capability for autonomous crew operations on the Moon and Mars.

The great distances between the Earth and Mars, and the associated time delays in communication make real time control of mission operations from Earth difficult. While the Apollo missions to the moon were scripted minute-by-minute, long-duration missions on the Moon and Mars will need to be more goal oriented on a weekly or monthly basis. Crews on the surface of the Moon or Mars should be able to plan and adjust their work and exploration schedule based on discoveries made in the field, or the lack of progress made on current investigations or operations.

Areas where Earth based testing or previous space testing have been extensive were rated low. Medium areas would benefit from validation or verification at the Moon. A high priority was given to a full mission simulation on the Moon to reduce risk.

<u>Investigation A</u>: Test integrated system health management techniques to autonomously monitor system performance and remedy repairs to underperforming systems with little or no crew intervention.

> ***Time Phasing***:
> **Not Applicable:** Continuing development of already mature technology.
>
> ***Priority***: Low
>
> ***Rationale***: Investigations can rely on heritage systems or earth developed technologies to provide Mars required capability.

<u>Investigation B:</u> Test crew-centered planning and scheduling techniques to allow exploration crews tactical control of their workload.

> ***Time Phasing***:
> **Not Applicable:** Continuing development of already mature technology.
>
> ***Priority***: Low
>
> ***Rationale***: Investigations can rely on heritage systems or earth developed technologies to provide Mars required capability.

<u>Investigation C</u>: Test automated sampling documentation techniques.

<u>Preamble</u>: Techniques tested under this Investigation will allow crews to quickly document all steps involved in the acquisition and curation of geologic samples on the Moon or Mars.

Time Phasing:
Early → Late: Techniques and technologies will continue to be matured starting with initial lunar sampling.

Priority: Medium

Rationale: Planetary protection drives unique requirements that would greatly benefit from lunar testing and evaluation. MER and in the future MSL will also add to this knowledge base for Mars specific sampling.

Investigation D: Test the execution of mission operations.

Preamble: This Investigation will include extravehicular activities (EVA) and intravehicular activities (IVA) without the control from Earth.

Time Phasing:
Middle → Late: Lunar experience from extended duration missions will add to the dataset.

Priority: Medium

Rationale: Earth provides the best testbed for development of these techniques. However, the Moon will play a role in moving toward more remote operations versus current LEO operations model.

Investigation E: Conduct a Mars surface mission simulation on the Moon.

Preamble: Simulation should address the degree of autonomy and self sufficiency that will be expected for Mars surface missions. The simulation should last >500 days without logistics resupply.

Time Phasing:
Late: Substantial lunar infrastructure that duplicates Mars system requirements would be necessary.

Priority: High

Rationale: Prior to committing astronauts to a multi-year journey to Mars a rigorous lunar mission simulation could greatly reduce risks associated with these missions.

Objective FF-B-2: Develop the capability for productive and efficient human-robotic interaction in the exploration of planetary surfaces.

Robotic explorers can be used to augment and compliment the explorations of human crews, thus making more efficient use of astronaut time for complex tasks that require human cognitive skills and dexterity.

Investigations can rely on heritage systems or earth-developed technologies to provide Mars required capability.

Time Phasing and Prioritization are the same for each Investigation.

Time Phasing:
Not Applicable: Continuing development of already mature technology.

Priority: Low

Rationale: Investigations can rely on heritage systems or earth-developed technologies to provide Mars required capability.

Investigation A: Test teleoperation techniques to allow human crews on the lunar or Martian surface to control and direct robotic explorers.

Investigation B: Test robot interface techniques that will allow human crews on the lunar or martian surface to operate a multitude of different types of robots with a single computer interface.

Investigation C: Test field geology tools/instrumentation that can enable significant in-situ field analysis of geological samples.

Preamble: This Investigation will establish methods for achieving the best accuracy/precision, diversity (results confirmable by alternate methods), minimize power/mass/volume requirements, maximize reliability, calibration (positive and negative control standards). Test field instrumentation capable of determining differences in samples based on subtle chemical and mineralogical differences in rocks and soils, sampling tools that can penetrate and sample deep enough into rocks to get below the chemically altered outer layer.

Investigation D: Test field geology research techniques, including Analysis Adaptability (not limited by prior hypothesis).

Objective FF-B-3: Establish an administrative structure and cost effective surface systems to facilitate strong international cooperation.

Although many Earth based programs have addressed these concerns and ISS has been a large scale NASA multi-lateral cooperation effort – further development of these collaboration concepts on a lunar program would be valuable.

<u>Investigation A</u>: Establish a set of export control laws and regulations that will enhance effective global cooperation on lunar activities.

> ***Time Phasing***:
> **Middle → Late:** Most benefit would come from a substantial multi-national integrated lunar program.
>
> ***Priority***: Low
>
> ***Rationale***: Although many Earth based programs have addressed these concerns and ISS has been a large-scale NASA multi-lateral cooperation effort – further development of these collaboration concepts on a lunar program would be valuable.

<u>Investigation B</u>: Establish standards and common interface designs to enable interoperability of systems developed by a global community.

> ***Time Phasing***:
> **Middle → Late:** Most benefit would come from a substantial multi-national integrated lunar program.
>
> ***Priority***: Low
>
> ***Rationale***: Although many Earth based programs have addressed these concerns and ISS has been a large-scale NASA multi-lateral cooperation effort – further development of these collaboration concepts on a lunar program would be valuable.

<u>Investigation C</u>: Establish a global partnership framework to enable all interested parties to participate in exploration activities.

<u>Preamble</u>: This process should enable varied levels of participation based on the capabilities, experience, goals and funding availability of each participating nation.
–*<u>Sub-Investigation 1:</u>* Initiate global participation in a robust robotic lunar exploration program
–<u>Sub-Investigation 2:</u> Initiate global participation in the early planning stages for human lunar exploration to establish a process for engaging a global community in the development process.

> ***Time Phasing***:
> **Middle → Late:** Most benefit would come from a substantial multi-national integrated lunar program.
>
> ***Priority***: Low
>
> ***Rationale***: Although many Earth based programs have addressed these concerns and ISS has been a large-scale NASA multi-lateral cooperation effort – further development of these collaboration concepts on a lunar program would be valuable.

<u>Investigation D</u>: Develop cost effective surface systems that can be developed in a relatively short period of time.

<u>Preamble</u>: The ISS development timeline/cost of 30 years and ~$100B will not be acceptable for Mars mission surface habitation development.

> ***Time Phasing***:
> **Early:** Early planning for lunar program needs to incorporate cost-effective approaches.
>
> ***Priority***: High
>
> ***Rationale***: Changes in NASA approach to large scale human exploration are required to enable human Mars missions. The lunar program is uniquely positioned in time to gain this experience.

<u>Goal FF-C</u>: Preparing for Future Missions to Other Airless Bodies.

<u>Purpose</u>: Establish the Airless Body mission risk reduction that could result from a lunar exploration program. Risk reduction includes the development and evaluation of technologies, systems, operational processes and techniques that could reduce the cost, schedule or technical risk associated with planning and executing robotic or human missions to other airless bodies. For this report, "Airless Bodies" includes Near Earth Objects (NEOs) as well as Phobos, Deimos, comets and the planet Mercury
.
The following evaluation criteria will be used to establish the priority for candidate ideas:

- <u>Airless Body Mission Risk Reduction Value</u>: How well do the candidates address the key risk reduction areas identified through NASA's Airless Body robotic and human mission planning studies?
- <u>Lunar Platform Value</u>: Do candidates leverage the unique attributes of a lunar program to achieve success – or – would other platforms be more effective from a technical/cost perspective?

The proposed timing for individual investigations is driven by the lunar capabilities/infrastructure required to enable the specific investigations. The proposed timing does not assume a specific timeline or phasing of Airless Body missions.

<u>Objective FF-C-1</u>: Ability to operate on a geologic surface.

<u>General Requirements:</u>

- Operate on a solid surface composed of dust, unconsolidated rock fragments, and bedrock lithologies

- Develop ability to characterize those materials, manipulate them, and, when needed, collect them.
- Develop mobility strategies for solid surface terrains.

<u>Investigation A</u>: Determine the distribution of volatile components

<u>Preamble</u>: Objective Sci-A-3 (characterize the environment and processes in lunar polar regions) will develop instruments and operational methods that will enhance our ability to map the distribution of volatile components on other airless bodies. The distribution of those components needs to be characterized to achieve science goals, to determine the resource potential of the objects, and to assess potential hazards that volatile reservoirs may have for robotic assets and crew. These volatiles may also reveal the chemical nature of impactors on the Moon through time.

Time Phasing:
Early to Middle: A mission by crew to a specific airless body will follow a robotic precursor mission to that body and occur after the development of relevant techniques on the Moon. This will include both orbital and surface investigations.

Priority: Medium.

Rationale: With crew on lunar surface one can repeatedly make the critical measurements and determine what works and why. The Moon can be used to test robotic techniques for identifying and mapping volatile deposits/distribution on other airless bodies. The lunar gravity may have an effect on volatile distribution and behavior, which keeps this from being a high priority, although the techniques used to map such deposits will be similar.

<u>Investigation B</u>: Evaluate the dynamical evolution and space weathering of the regolith.

<u>Preamble</u>: As outlined in Objective Sci-A-4, impacts produce a surface regolith on all planetary objects without atmospheres. Because regolith is an important part of local surface geology on such bodies, it is important to study the processes and products associated with them. Developing techniques to make appropriate measurements of those processes and products on the Moon will enhance our ability to make similar assessments on other airless bodies.

Time Phasing:
Early - Middle: Orbital remote sensing, surface lander characterization (i.e. Geotechnical). Comprehensive subsurface sampling (e.g., trenching, drilling, crater walls), geotechnical, ability to sample steep slopes, geophysical profiling, and telerobotic sampling of remote sites.

Priority: Medium to Low (dependent upon risk reduction)

Rationale: Use the Moon to develop the techniques to study and sample regolith and space weathering products. These techniques can then be adapted to study regolith from other airless bodies in different space weathering environments.

Investigation C: Understand impact processes

Preamble: Impact cratering is the dominant geologic process affecting planetary surfaces. Techniques devised for studying those processes on the Moon (Objective Sci-A-7) will enhance our ability to study similar structures on other airless bodies. Several of the scientific investigations under Objective Sci-A-7, however, can only be accomplished on the Moon or are better accomplished there. For example, complex craters will not exist on most NEOs (they are too small), so studies of their formation requires lunar exploration. Likewise, impact craters on NEOs will not have impact melt sheets (unless the NEO is a fragment from a larger body with an impact melt sheet), so studies of their formation also require lunar exploration. Because complex craters and impact melt sheets exist on Mars, evaluating them on the Moon (rather than NEOs) will be valuable for future Mars exploration.

Time Phasing:
Early - Middle: Map crater geology, compositions, geophysical state, robotic sample return, robotic surface mobility. Field studies of simple craters; sampling ejecta, bedrock in walls; geophysical profiling.

Priority: Medium - High

Rationale: Impact processes dominant the geological evolution on small airless bodies. Optimization of techniques to study impacts will enhance science return, but the techniques needed to access steep crater walls in a microgravity environment will be different from the Moon.

Objective FF-C-2: Develop the capability for autonomous crew operations.

(Corollary to Feed-Forward Objective FF-A-6)

This objective overlaps with Objective FF-B-1. The great distances between the Earth and Airless Bodies, and the associated time delays in communication will make real time control of mission operations from Earth difficult. While the Apollo missions to the moon were scripted minute-by-minute, long-duration missions on the Moon and other airless bodies with even greater light-time travel delays of 7 to 15 seconds or more will need to be more goal oriented on a weekly or monthly basis. Crews on the surface of the Moon or other Airless Bodies should be able to plan and adjust their work and exploration schedule based on discoveries made in the field, or the lack of progress made on current investigations or operations.

Areas where Earth-based testing or previous space testing have been extensive were rated low. Medium areas would benefit from validation or verification at the Moon. A medium to high priority was given to a full mission simulation on the Moon to reduce risk.

Investigation A: Test integrated system health management techniques to autonomously monitor system performance and remedy repairs to underperforming systems with little or no crew intervention.

Time Phasing:
Not Applicable: Continuing development of already mature technology.

Priority: Low

Rationale: Investigations can rely on heritage systems or Earth-developed technologies to provide Airless Body required capability.

<u>Investigation B:</u> Test crew-centered planning and scheduling techniques to allow exploration crews tactical control of their workload.

Time Phasing:
Not Applicable: Continuing development of already mature technology.

Priority: Low

Rationale: Investigations can rely on heritage systems or Earth-developed technologies to provide Airless Body required capability.

<u>Investigation C</u>: Test automated sampling documentation techniques.

<u>Preamble</u>: This is also related to investigations within Objective C-2. Techniques tested under this Investigation will allow crews to quickly document all steps involved in the acquisition and curation of geologic samples on the Moon, Mars, or Airless Bodies.

Time Phasing:
Early → Late: Techniques and technologies will continue to be matured starting with initial lunar sampling.

Priority: Medium

Rationale: Limited time at an Airless Body for any human crew requires that the time be used efficiently to gather and record as much information as possible.

<u>Investigation D:</u> Test the execution of mission operations.

<u>Preamble</u>: This Investigation will include extravehicular activities (EVA) and intravehicular activities (IVA) without the control from Earth.

Time Phasing:
Middle → Late: Lunar experience from extended duration missions will add to the dataset.

Priority: Medium

Rationale: Earth provides the best testbed for development of these techniques. However, the Moon will play a role in moving toward more remote operations versus current LEO operations model.

<u>Investigation E</u>: Conduct an Airless Body surface mission simulation on the Moon.

<u>Preamble</u>: Simulation should address the degree of autonomy and self-sufficiency that will be expected for Airless Body surface missions. The Moon affords a lower gravity environment, but not the micro-gravity environment of Airless Bodies.

> ***Time Phasing***:
> **Early to Middle:** The exploration of an Airless Body will be a relatively quick event. Limited infrastructure will be available so such mission scenarios could be conducted during the early phase of lunar exploration, although it is more likely to be during the middle phase once some critical lunar objectives have been addressed.
>
> ***Priority***: Medium to High
>
> ***Rationale***: Prior to committing astronauts to a long journey to an Airless Body a rigorous lunar mission simulation could greatly reduce risks associated with these missions.

<u>Investigation F</u>: Evaluate crew transit and EVA systems in a deep-space environment

<u>Preamble</u>: Missions to other Airless Bodies will involve the use of crew transport systems and EVA systems that could be evaluated as part of a lunar program.

> ***Time Phasing***:
> **Middle → Late:** Beginning with full lunar day missions, lunar crew transport systems would remain in a deep-space environment for month(s) durations. In addition, lunar crews travelling between the Earth and Moon will need to be prepared to perform deep-space EVAs.
>
> ***Priority***: Medium
>
> ***Rationale***: Prior to committing astronauts to a multi-month journey to another Airless Body a rigorous lunar mission evaluation of planned transit vehicles and EVA systems could greatly reduce risks associated with these missions.

<u>Objective FF-C-3</u>: Development and implementation of sample return technologies and protocols.

(Corollary to Feed-Forward Objective Sci-A-2)

A fundamental activity tied to the exploration of a planetary body is sampling its surface. Acquisition, storage, return, and curation of samples requires the development of protocols and technologies that allows selection of appropriate materials and protects their integrity. Investigations A-D in Objective Sci-A-2 are all relevant to other Airless Bodies.

Time Phasing:

Early: All investigations need to be started early.

Middle: Modify techniques as experience with *in situ* sample analysis improves and infrastructure develops.

Late: Continue to modify techniques as experience with *in situ* sample analysis improves and infrastructure develops.

Science Priority: Medium to High (enables high priority science).

Rationale: Protocols and technology developed for the Moon may reduce risk for similar sampling, handling, and curation of specimens from other Airless Bodies.

Investigation-A: Develop a sampling strategy for the Moon and other Airless Bodies

It is important to have a guiding strategy for the interplay of field observations by humans and by robotic devices with sample collection and documentation. On the Moon and other airless bodies it is critical to understand the geological style, including the nature of impact mixing at all scales, and the contribution of distant events to site geology. Determine which sample targets are appropriate for reconnaissance sampling versus detailed field study.

Investigation-B: Understand the scientific requirements for sample curation, packaging, and transport to Earth.

To make accurate analyses of geological samples collected on the surface, the samples must be kept clean from contamination by other samples, dust, and other human- or robotic-generated materials. It is also important to keep track of each one and its collection location to avoid confusion during later analysis. For successful planning, we must determine what analyses will be made on geological, materials science, and biological materials to establish appropriate controls on contamination.

Investigation-C: Understand what analyses (field and laboratory) need to be done on the Moon and other airless bodies to aid field studies and optimize the value of samples returned to Earth.

Develop reliable and largely automated analytical instruments for use on the planetary surfaces to screen samples to choose which to return to Earth. It is crucial to determine the optimal types of analyses and instruments.

Investigation-D: Enhance curatorial facilities on Earth to handle environmentally-sensitive samples (e.g., ices)

For the Moon and other airless bodies, it may be necessary to transport environmentally-sensitive samples to Earth for detailed analysis. Examples include volatiles and ices from the surface and near-surface of airless bodies. Thus, sample packaging and transport methods and equipment need to be designed and implemented. Once received on Earth, they must be curated under appropriate conditions.

Objective FF-C-4: Understand planetary differentiation.
(Corollary to Feed-Forward Objective Sci-A-5)

The Moon is a small, differentiated planet that is geologically more complex than the smaller NEOs. The Moon presents the best opportunity to geochemically characterize early fundamental processes in a planetary body of substantial size.

Investigation A: Examine the diversity of Airless Bodies within a planetary differentiation context.

Preamble: Carrying out investigations tied to understanding lunar differentiation (Objective Sci-A-5, Investigations A-E) have limited relevance to other airless bodies, but these investigations require the robotic and/or human return of surface materials and the emplacement of regional and planetary network stations for long term monitoring of surface conditions and geophysical properties. Emplacement of networks on NEOs would be instrumental in quantifying structure (regolith thickness, assembly, internal components) and composition, monitoring current impact fluxes, and recording changes in surface conditions-processes.

Time phasing (applies to all Investigations):
Early- Middle: Remote sensing of rock types, robotic sample return, regional-global networks.

Science Priority: Medium to Low, reduce risk in deployment,

Rationale: Understand Planetary formation processes and geological history.

Objective FF-C-5: Regolith as a recorder of Solar-System processes.
(Corollary to Feed-Forward Objectives Sci-A-4 & Sci-B-2)

Preamble: The regolith contains information about the history of the Sun, variations in cosmic ray flux, astronomical events such as supernova and gamma-ray bursts, changing compositions of impactors with time, and possibly even the nature of the early Earth. It is a complicated record, but long-term investigations can shed light on important issues in planetary science and astronomy.

Time Phasing (applies to all Investigations):
Early: Identify targets for future surface exploration from remote data (magnetic anomalies, paleoregoliths).
Middle: Precision sampling of regolith at different stratigraphic levels, identify and sample paleoregolith.
Late: Precision sampling of regolith at different stratigraphic levels, identify and sample paleoregolith at new and wider areas; potential ISRU tie-in for extralunar material search.

Science Priority: High

Rationale: Use Airless Body exploration to characterize the history of the inner Solar System and the galaxy and compare/contrast with similar regolith studies on the Moon.

Investigation-A: Assess temporal variations in the Sun through studies of solar wind and solar flare products in the regolith

Study the records of past solar particles and irradiance, and galactic cosmic rays preserved in lunar regolith. This work involves searching for identifiable layers of "fossil regolith" that can be dated to track changes in the Sun and galactic cosmic rays through time. This objective is synergistic with use of the lunar regolith as an in situ resource and with use of the Moon as a platform for heliophysics observations. Regolith preserves the composition and flux of solar wind particles potentially over the past ~4 billion years, a record that may elucidate the evolution of the sun and the sources of cosmic rays.

Time Phasing: **Early-Middle**

Investigation-B: Assess variability in the solar constant through detailed, long-term heat flow measurements

In principle, borehole temperature measurements can be used to determine the solar constant as a function of time over the last hundreds to thousands of years. Climate reconstruction from subsurface temperatures is a well-developed technique for Earth. Variability in the solar constant is an important input parameter for models of terrestrial paleoclimate.

Time phasing: **Early.**

Investigation-C: Assess variations in cosmic radiation through time

Variations in the dose of cosmic radiation through time, including from supernova, may be recorded in grains in the regolith. This requires detailed sampling and measurements of radiation damage and cosmic ray products in the regolith.

Time phasing: **Middle-Late.**

Objective FF-C-6: Develop the capability for human crews to operate safely on planetary surfaces, protected from the extreme environment and hazards.

(Corollary to Feed-Forward Objectives Sci-D-11, Sci-D-14, Sci-D-18)

This objective overlaps with Objective FF-A-9. Due to the lack of measurable magnetic fields and the existence of thin or very tenuous atmospheres, humans working and living on the Moon will be immersed in environments with higher levels of radiation and micrometeoroid impacts than on Earth. Long duration missions to Airless Bodies will encounter similar risks related to micrometeroids, solar wind particles and cosmic rays. On the other hand, secondary particles coming back off the lunar surface add an additional element that does not strictly mimic the environment that will be seen during Airless Body missions. In addition, due to the motion of the Moon with respect to the Sun, Any specific location on the Moon will only experience solar wind impingement for ~14 days/month as opposed to the constant flux that will be seen during Airless Body missions.

<u>Investigation A</u>: Test radiation shielding technologies.

<u>Preamble</u>: This Investigation is essential for protecting astronauts and their equipment on the lunar surface from galactic cosmic rays (GCR) and solar energetic particle (SEP) events. It involves the return to Earth for analysis materials that are being considered for radiation shielding.

> ***Time Phasing***:
> **Early:** Data points collected from early robotic and human lunar missions could be valuable in informing design decision for Airless Body missions.
>
> ***Priority***: High
>
> ***Rationale***: ISS is within the Van Allen belts protecting the crews/equipment from most radiation. In addition, although LDEF and other satellites/components (e.g., HST solar arrays, thermal blankets) have been returned to Earth for analysis of radiation degradation, only a limited amount of equipment (e.g., the Surveyor 3 camera recovered by Apollo 12) has ever been returned from outside the Earth's magnetosphere. Since decisions on the type and thickness of shielding can have a major impact on the mass of space vehicles, information from materials exposed to the deep space radiation at the Moon would be valuable in optimizing the design of Airless Body missions. There are a few differences in the lunar radiation environment versus the environment of missions to other Airless Bodies that need to be taken into consideration, including: 1) Lunar surface based equipment will not be exposed to the same GCR flux since the Moon is block half the flux at any time, 2) Same is true of the Solar wind flux which is blocked during the two week lunar night each month, 3) Secondary flux (neutrons) coming off the lunar surface add to the overall radiation flux – a factor which will be non-existent or different on other Airless Body missions.

<u>Investigation B</u>: Test micrometeorite protection technologies to prevent damage caused by micrometeorite impacts.

<u>Preamble</u>: This Investigation will leverage ISS experience to determine if additional technological advances are required to support ~180 day round trips to NEOs.

> ***Time Phasing***:
> **Early → Late:** Data can be collected during all lunar surface stays.
>
> ***Priority***: Low
>
> ***Rationale***: ISS and other orbiting assets have provided a good database of micrometeoroid and orbit debris impact affects that can be used to establish Airless Body transit vehicle shielding requirements. Lunar missions will add to this dataset particularly during lunar exploration phases where round-trip flights will enable the return of shielding materials for analysis. Similar to the radiation shielding discussion,

the reduction in flux due to the shielding of the Moon itself versus the full flux that will impact other Airless Body missions would need to be factored into the analysis.

<u>Investigation C</u>: Establish space weather modeling, forecasting and monitoring capabilities.

<u>Preamble</u>: The capabilities established under this investigation can be used to warn Airless Body transit/surface crews of potentially hazardous solar events. The goal of these systems should be to provide as early a warning as possible of dangers.

Time Phasing:
Early → Late: Information is needed early in the Airless Body transit/surface vehicle design phase. Although there are many current sources of data (Earth orbiting satellites, Earth-Sun L1 satellites) data collected from lunar missions will add to this data set.

Priority: Low

Rationale: Does not rely on a lunar program as a key way of developing this capability to support missions to other Airless Bodies. Planning for other Airless Body missions may actually provide information that could be used in lunar surface system designs since Airless Body mission will have stricter mass requirements, longer single mission duration requirements and will lack in-situ resources that can be used for shielding by lunar missions.

<u>Investigation D</u>: Establish dust/electrostatic mitigation technologies.

<u>Preamble</u>: This is related to Objective Sci-A-1. The hazard of dust in the airless body environment to humans and critical (life support and exploration) systems has to be mitigated to reduce risk of missions to airless bodies. The Moon is the ideal test bed for such technologies developed on Earth using simulants.

Time Phasing:
Early → Late: Some data can be gleaned from the Apollo data and using simulants, but need to be tested in a realistic environment. As such, this investigation covers all stages of a lunar exploration program.

Priority: High

Rationale: Information on dust/electrostatic mitigation is needed early in the Airless Body mission system design.

<u>Objective FF-C-7</u>: Develop the capability for productive and efficient human-robotic interaction in the exploration of planetary surfaces.
(Corollary to Feed-Forward Objective FF-B-2)

This objective overlaps with Objective FF-B-2. Robotic explorers can be used to augment and compliment the explorations of human crews, thus making more efficient use of astronaut time for complex tasks that require human cognitive skills and dexterity.
Investigations can rely on heritage systems or earth-developed technologies to provide Airless Body required capability.
Time Phasing and Prioritization are the same for Investigations A-C.

Time Phasing:
Not Applicable: Continuing development of already mature technology.

Priority: Low

Rationale: Investigations can rely on heritage systems or Earth-developed technologies to provide Airless Body required capability.

<u>Investigation A</u>: Test teleoperation techniques to allow human crews on the lunar or Airless Body surface to control and direct robotic explorers.

<u>Preamble</u>: This Investigation is important for risk reduction of human missions to Airless Bodies. The surface environment may preclude human EVA, requiring teleoperation of robotic systems.

<u>Investigation B</u>: Test robot interface techniques that will allow human crews on the lunar or Airless Body surface to operate a multitude of different types of robots with a single computer interface.

<u>Preamble</u>: Increased exploration efficiency is essential for maximizing the limited time that crews will have at an Airless Body.

<u>Investigation C</u>: Test field geology tools/instrumentation that can enable significant in-situ field analysis of geological samples.

<u>Preamble</u>: This Investigation will establish methods for achieving the best accuracy/precision, diversity (results confirmable by alternate methods), minimize power/mass/volume requirements, maximize reliability, calibration (positive and negative control standards). Test field instrumentation capable of determining differences in samples based on subtle chemical and mineralogical differences in rocks and soils, sampling tools that can penetrate and sample deep enough into rocks to get below the chemically altered outer layer.

<u>Investigation D:</u> Test robotic field assistant technologies.

<u>Preamble</u>: These are required to complement and augment the abilities of IVA and EVA crew members exploring or working on Airless Bodies.

Time Phasing:
Middle → Late: Continuing development of already mature technology. However, lunar missions will add to this dataset so that this technology can be improved in an evolutionary manner.

Priority: Low

Rationale: Investigations can rely on heritage systems (e.g., ISS, STS) or earth developed technologies (e.g., Department of Defense) to provide Mars required capability.

<u>Investigation E</u>: Test advanced space suit technologies.

<u>Preamble</u>: New space suit technologies must allow greater mobility, dexterity, and range than the space suits used during the Apollo, Space Shuttle, and International Space Station programs. Suits systems that are applicable for long term use in a deep-space environment (e.g., radiation, thermal) need to be developed.

Time Phasing:
Early → Late: Timing is driven by when the capability would be required for lunar applications since these technologies would be supporting lunar activities – not – done specifically as Airless Body technology demonstrations.

Priority: Medium

Rationale: Space suit technologies have been matured with past human space programs. However, lunar missions will add to this dataset so that this technology can be improved in an evolutionary manner with a focus on increased flexibility, mobility and dexterity as well as design for deep space operation (enabling EVA not only on the lunar surface but during Earth-Moon transit). Much of this work would have applicability to other Airless Body missions.

<u>Investigation F</u>: Testing exploration systems under different lighting conditions.

<u>Preamble</u>: It is likely that Airless Body exploration will need to be conducted under changing lighting conditions that could be far more variable than on the Moon. While the Moon has relatively constant lighting conditions over periods of Earth days, systems can be tested under controlled changes of lighting conditions in a similar environment, but in a controlled manner moving from lighted areas to those of full shade.

Time Phasing:
Early → Middle: Robotic exploration can begin this investigation, which can then be advanced to systems that support human exploration.

Priority: High

Rationale: The Moon is the best place to test such technologies for the exploration of Airless Bodies.

<u>Objective FF-C-8</u>: Develop Crew Health Systems that enable safe, long duration, missions
(Corollary to Feed-Forward Objective FF-A-2)**.**

<u>Investigation A</u>: Test medical diagnosis and treatment technologies and techniques.

<u>Preamble</u>: This investigation supports the development of well-patient care in addition to the treatment of illnesses/injuries on long duration human missions. Since missions to airless bodies can last in duration up to one year, with some missions having constrained abort-to-Earth options, the self sufficiency of the crew to maintain their health and to deal with medical emergencies will need to be much greater than the current Shuttle and ISS systems where a rapid return to Earth is possible.

> ***Time Phasing***:
> **Middle → Late:** Valuable data will be collected during extended surface stays.
>
> ***Priority***: Low
>
> ***Rationale***: Telemedicine, minimally invasive techniques and remote health care are technology areas being matured on Earth. However, lunar research will develop flight qualified systems that will have some applicability to other long duration missions. For missions to small airless bodies there could be significant differences in the packaging of these technologies with crews spending the entire mission in mass/volume/power constrained transit vehicles when compared with a long duration lunar outpost and there may also be differences in systems and processes developed for use in a partial-gravity environment and those required for zero-gravity missions. Even with these difference factored in there would still be some applicability to lunar research in this area.

<u>Investigation B</u>: Test long-term consumable storage technologies.

<u>Preamble</u>: This investigation is required to better understand how to protect stored consumables required to support long duration crewed missions in a high radiation environment. Water, oxygen, food and other crew required consumables will need to be stored over long periods to support extended lunar surface stays. Lessons learned from lunar exploration will provide input to optimizing storage methods to minimize container mass/volume while ensuring that the quality of consumables remains unchanged throughout the storage period.

> ***Time Phasing***:
> **Middle → Late:** Data can be collected during extended surface stays.
>
> ***Priority***: Low
>
> ***Rationale***: Experience on Earth and in Space (ISS) has been significant. However – the lunar radiation environment effects on shelf life could inform operational protocols for long duration airless body missions.

<u>Investigation C</u>: Perform psychological health research on impact of extreme isolations.

Time Phasing:
Middle → Late: Data can be collected during extended surface stays.

Priority: Low

Rationale: Research on earth and space based (ISS, Skylab, Mir, Salyut) isolated environments has been significant although lunar missions represent a more remote/isolated environment versus the Earth-orbit missions. But, there will be a number of differences between lunar mission profiles and other airless body missions that will make lunar data only partially applicable, including: 1) The perception of a possibility of a ~4 day return to Earth in an emergency for lunar missions versus month or more minimal return time options for missions to other airless bodies, 2) The fact difference between having a large image of the Earth in the sky at lunar distances versus the small blue dot that crews at further distances will see.

Objective FF-C-9: Establish an administrative structure and cost effective surface systems to facilitate strong international cooperation.

(Corollary of Feed-Forward Objective FF-B-3)**.**

Although many Earth based programs have addressed these concerns and ISS has been a large scale NASA multi-lateral cooperation effort – further development of these collaboration concepts on a lunar program would be valuable.

Investigation A: Establish a set of export control laws and regulations that will enhance effective global cooperation on lunar activities.

Time Phasing:
Middle → Late: Most benefit would come from a substantial multi-national integrated lunar program.

Priority: Low

Rationale: Although many Earth based programs have addressed these concerns and ISS has been a large-scale NASA multi-lateral cooperation effort – further development of these collaboration concepts on a lunar program would be valuable.

Investigation B: Establish standards and common interface designs to enable interoperability of systems developed by a global community.

Time Phasing:
Middle → Late: Most benefit would come from a substantial multi-national integrated lunar program.

Priority: Low

Rationale: Although many Earth based programs have addressed these concerns and ISS has been a large-scale NASA multi-lateral cooperation effort – further development of these collaboration concepts on a lunar program would be valuable.

Investigation C: Establish a global partnership framework to enable all interested parties to participate in exploration activities.

Preamble: This process should enable varied levels of participation based on the capabilities, experience, goals and funding availability of each participating nation.
–*Sub-Investigation 1:* Initiate global participation in a robust robotic lunar exploration program
–Sub-Investigation 2: Initiate global participation in the early planning stages for human lunar exploration to establish a process for engaging a global community in the development process.

Time Phasing:
Middle → Late: Most benefit would come from a substantial multi-national integrated lunar program.

Priority: Low

Rationale: Although many Earth based programs have addressed these concerns and ISS has been a large-scale NASA multi-lateral cooperation effort – further development of these collaboration concepts on a lunar program would be valuable.

Investigation D: Develop cost effective surface systems that can be developed in a relatively short period of time.

Preamble: The ISS development timeline/cost of 30 years and ~$100B will not be acceptable for future human mission system development.

Time Phasing:
Early: Early planning for lunar program needs to incorporate cost-effective approaches.

Priority: High

Rationale: Changes in NASA approach to large scale human exploration are required to enable human Mars missions. The lunar program is uniquely positioned in time to gain this experience.

<u>Objective FF-C-10</u>: Develop the capability to acquire and use local resources to sustain long-term exploration crews.
(Corollary of Feed-Forward Objective FF-A-4)**.**

Some Airless Bodies possess abundant natural resources that could be used to supply human consumables, such as air and water. Relying on earth-based supplies for long duration Airless Body missions is likely neither affordable or sustainable, and achieving a certain level of self-sufficiency would also reduce the risks involved with the delivery of those supplies. Differences in lunar and other Airless Body environments will drive toward different technology solutions for resource utilization – but there are some areas where lunar experience will have applicability to the design of systems for use on other Airless Bodies.

<u>Investigation A</u>: Test resource identification/characterization procedures and technologies.

Time Phasing:
Early → Late: Beginning with early robotic lunar missions, information on system perform in identifying and characterizing resources could have applicability to other Airless Body missions.

Priority: Low

Rationale: Various existing missions including the Mars robotic program is and will continue to validate technologies for identifying and characterize planetary resources. Lunar experience will add to this database.

<u>Investigation B</u>: Test technologies to produce water from frozen regoliths.

Time Phasing:
Middle → Late: Timing driven by lunar applications (only if a permanently shadowed polar location is selected for a robotic or human mission).

Priority: Medium

Rationale: For specific Airless Body being investigated that may contain trapped water – the differences between how this water is trapped versus how it is trapped on the Moon will factor into the applicability of lunar technologies. In addition, lunar developed technology designs may rely on a partial-gravity environment.

<u>Investigation C:</u> Test product storage technologies.

Time Phasing:
Middle → Late: Experience would be gained during the period when crew are present on the lunar surface for extended stays.

Priority: Low

Rationale: Differences between the lunar surface environment and other Airless Body mission environments (e.g., thermal, gravity) need to be taken into account.

<u>Objective FF-C-11</u>: Establishment of in-situ resource utilization systems.

(Corollary to Feed-Forward Objectives Sust-A-3, Sust-B-9)

This is related to Objective Sust-B-9. Production and recycling of mission consumables including oxygen, water, carbon-based fuels, and various laboratory gases are a key element of sustainably reducing the mass and cost risk associated with the logistical supply of materials brought from Earth. Reliable production of mission consumables and the sustainable cost savings they represent might be among the most important contributions from the lunar experience to human and robotic exploration of the Solar System.

Substantial interaction is inherently required between systems that produce such consumables and the systems that use them, implying the need for substantial system engineering efforts early in the development of lunar surface systems. Additionally, early demonstrations of these capabilities are essential for them to be incorporated into the planning of science and exploration activities in a mission critical role. The urgency of early demonstrations is amplified by the necessity of affecting the design of early robotic and human systems that could be initiated well before the return of humans to the moon.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:

<u>Early</u>: Conduct demonstrations of oxygen production and storage from lunar regolith at the largest affordable scale of capacity. Conduct detailed system engineering of human and robotic systems on the moon incorporating realistic assumptions of oxygen and water production.

<u>Middle:</u> Demonstrate and utilize full-scale production of oxygen and water in sufficient capacities to meet life support, radiation-protection, and power system needs. Demonstrate production of carbon-based fuel using recycled waste.

<u>Late:</u> Utilize locally produced oxygen, water and fuel to eliminate logistics supply of consumables from Earth

Priority: High (Early and Middle), Medium (Late)

Rationale: Sustainable support for human and robotic scientific investigation and exploration activities depends on reducing the cost of operations. Production of mission consumables such as oxygen, water and carbon-based molecules as fuel will dramatically reduce the cost of logistical supply from Earth.

Investigation A: Demonstrate small-scale robotic production and storage of oxygen from reduction of lunar regolith.

Investigation B: Demonstrate hydrogen/water production techniques including extracting polar water/ice/volatiles in permanently shadowed craters, solar wind volatiles, trash processing, and propellant scavenging.

Investigation C: Develop multiple oxygen production from regolith techniques.

Investigation D: Develop and deploy full-scale production of life support consumables, including oxygen and water, fully integrated with life support systems.

Investigation E: Develop and deploy full-scale production of power system reagents fully integrated with surface power systems.

Investigation F: Develop carbon production or extraction techniques including solar wind volatiles, trash processing, and composite material processing.

Investigation G: Develop retrieval of other valuable atomic/molecular species through recycling of waste.

Investigation H: Develop and deploy production of carbon-based fuels from recycled waste streams.

<u>Sustainability (Sust) Theme</u>: Extend Sustained Human Presence to the Moon to Enable Eventual Settlement

The fundamental purpose of activity involving the Moon is to enable humanity to do there permanently what we already value doing on Earth: science, to pursue new knowledge; exploration, to discover and reach new territories; commerce, to create wealth that satisfies human needs; settlement, to enable people to live out their lives there; and security, to guarantee peace and safety, both for settlers and for the home planet. Achieving permanent human presence depends on ensuring that profitable, economically self-sustaining commercial endeavor will develop wherever possible and ethically appropriate. Activities not within the commercial domain must define and produce value sufficient to justify continuing government and nonprofit funding. Initial human and robotic presence must lay a solid foundation in science and technology demonstrations, showing the value of extended and expanded presence, so that our opportunity to live and work on the Moon need never end.

Proceeding with the human exploration and settlement of the moon will occur based on political decisions, public and private economic decisions, and science community decisions. While individual tolerance for ongoing governmental subsidy and control of lunar exploration varies widely, it is certainly affected by perceptions of the return of value from exploration activities. The return of value is an individual judgment and might include factors as diverse as scientific discovery, technology developments with terrestrial application, the opportunity costs of lunar exploration, and how long it might take until the lunar exploration enterprise is commercially self-sustaining. The constituency for human lunar activity has the burden of proving the value of science and terrestrial commercial spinoffs compared to the opportunity costs, and helping to organize the enterprise in such as way as to minimize the time to self-sufficiency.

The Sustainability Theme within the Lunar Exploration Roadmap has many dimensions that share the unifying notion that *sustained* lunar activities are only possible when they are *sustainable* through ongoing return of value, realized and anticipated, from those activities. The long-term objective of permanent human presence in the form of a self-sustained settlement is the titular purpose of the elements described in this theme, but such an objective is most readily defensible when strongly linked to the sister themes of science and feeding forward of the lunar experience to the human exploration of other destinations in the solar system. Therefore, the direct mingling of science and exploration goals and objectives is explicitly made in this theme of the roadmap. The role of commercial activity as an indispensible aspect of sustainability is self-evident in times when the limits of governmental support are so apparent, but the effective integrated phasing of initiatives across all the themes, goals and objectives is at the core of establishing a sustainable expansion of human presence away from Earth.

<u>Goal Sust-A</u>: Maximize Commercial Activity

The goal of maximizing commercial activity includes those actions necessary to ensure that economically self-sustaining commercial endeavor is employed except where inherently governmental activity is necessary. Sustainability and growth of lunar presence will require that resources come not only from government but also from the private sector. Public-private partnerships are needed to ensure that government activity facilitates to the greatest extent the development of commercial and other private-sector initiatives. Encouragement of entrepreneurship and private investment will play a key role in fueling innovation and economic expansion, and enable NASA to focus resources toward human exploration beyond the Moon.

Formulating a roadmap with an outcome of commerce fully integrated into the scientific study and exploration of the moon includes decisive action on the part of the governmental entities early and throughout the expansion of lunar activity to remove obstacles to commercial activities, including activities not anticipated by governments, and foster the transfer of providing goods and services initiated in the public sector to the private sector.

The aggregation and integration of technical and resource needs of all the participants in the return to the moon is one of the main intents of the Lunar Exploration Roadmap at large, but a central principle guiding the incorporation of commercial participation. Integrated needs can provide opportunities for efficiently delivered commercial products and services with a market of sustainable size and at the earliest point in time. Aggregating needs across the spectrum of scientific disciplines and the diverse exploration objectives will involve focusing the definition of missions to define essential capabilities, relinquishing control by any single activity over the definition of a capability in order to consider other users' needs, and combining resources to obtain the capability. Aggregated needs could be expected to lower the cost to each user group, accelerate the scheduled availability of capabilities, and potentially expand the set of capabilities that are provided. One of the main challenges to aggregating needs is institutional, requiring the collaboration between sometimes-competing organizations such as NASA mission directorates, universities, and international agencies and corporations. Perhaps one of the main benefits may be the experience gained in preparation for the far greater challenge of organizing the exploration of Mars using an established space commerce activity developed as part of the return to the moon.

There is precedent in policy within the US for commercial integration into space science and exploration, namely the ESMD Commercial Development Policy & Implementation Plan (now in force), and the OSTP Technology Priorities (see OSTP web mentioning NASA in this context).

The objectives described in this Goal provide a roadmap for the integration of commercial activity into the broader context of the return to the moon, including aspects that touch on international utilization of commercial activity. The first objective suggests key steps that much be taken at the governmental level to encourage commercial activity. The remaining objectives are time phased to indicate how commercial activity is gradually integrated into the broader lunar activity picture.

<u>Objective Sust-A-1</u>: Establish policies and implementation of comprehensive, coordinated governmental and intergovernmental action to foster space commerce.

The risks involved in re-initiating activities on the moon are sufficiently large as to form a barrier to the entry of commercial ventures into those activities. At the very top level, these risks include the safety and well being of humans on the moon to live and work, and the effective functioning of hardware and software systems involved in scientific and exploration tasks. Government's primary role in the return to the moon is the reduction of these risks through extensive development and operational testing of technology and collection of scientific and engineering data characterizing the moon and it's potential for exploitation. As those risks are reduced to levels acceptable to commercial investment, government support for these activities should be replaced by the efficiencies of the marketplace through a fair and open exit strategy emplaced early and through international agreement on it's nature and implementation.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:

Early: Clarify and reduce the treaty, legal, regulatory and policy barriers to space commerce before the technology standards and mission architecture decisions about the return to the moon are finalized. Evolve and implement engineering standards for lunar systems and organizational structures to facilitate collaborative lunar activities.

Middle: Establish and administer an international regulatory framework for space commerce.

Late: Transition control of planning and operations of lunar activities initiated with government support to private commerce, including initial assurance of minimum government customer base.

Priority: High

Rationale: An international commercial involvement strategy must be in place before the government-only approaches are entrenched in order to avoid precluding commercial activities. The constraints imposed by international legal and regulatory framework for space commerce will strongly affect the economics of commercial ventures. Since successful ventures have considerable lead times, a stable regulatory framework, established early, permits appropriate entry into the space commerce market. Once the legal and regulatory framework is established for space commerce, transparent processes must be established and administered to maintain and execute it.

Initiative A: Negotiate an international agreement promoting use of commercial products and services by both government and non-government customers, whenever possible and appropriate.
Initiative B: Clarify the international legal and regulatory framework addressing all activities relevant to commerce including property rights, liability, dispute resolution, etc.
Initiative C: Establish an international administrative organization that ensures the legal and regulatory framework is observed.

Objective Sust-A-2: Preparation for Commerce I: Conduct a comprehensive resource and market assessment of commercial support for scientific and exploration activities on the Moon.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:

Early: In regions considered to be of the highest scientific and exploration value, conduct increasingly precise mapping, prospecting and assaying of lunar surface physical resources including minerals and surface volatiles. Identify communications and navigation network options

Middle: Broaden the geographical extent of detailed resource mapping, prospecting and assaying of lunar surface physical resources, including commercially provided services.

Priority: High

Rationale: Establishing the resource potential, including concentrations of high value materials is a fundamental aspect of commercial viability of resource exploitation and product delivery.

Initiative A: Identify linkages between lunar surface science goals and objectives and resources related to early exploitation for production of oxygen, water and other mission consumables.
Initiative B: Identify sites for detailed mapping, prospecting and assaying of resources and the feasibility of extraction options.
Initiative C: Develop standards for lunar surface mapping; prospecting and assaying that can realize savings in fleets of commercial robots.

Objective Sust-A-3: Preparation for Commerce II: Conduct small-scale demonstrations of potentially commercial lunar support services for scientific and exploration activities on the Moon.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:

Early: Demonstrate extraction and processing of lunar resources to produce mission-enabling commodities such as oxygen and water. Demonstrate effective surface communications and navigation networks.

Middle: Demonstrate extraction and processing of lunar resources to produce feedstock materials for lunar manufacturing.

Priority: High

Rationale: Feasibility demonstrations of local production of valuable commodities and communication/navigation services substantially build confidence in the marketability of lunar commerce and provide essential learning opportunities for scaling up production and service networks to pilot plant levels. Because the risk involved in these demonstrations is large, this objective is most likely supported by government, but may be executed by commercial entities.

Initiative A: Conduct the earliest possible demonstration of lunar surface production of oxygen, water and other mission consumables, using multiple technical approaches to raw material collection and processing.
Initiative B: Conduct the earliest possible demonstration of commercially provided communication and navigation systems on the lunar surface.

Objective Sust-A-4: Transition to Commerce I: Conduct pilot-plant scale demonstrations of potentially commercial lunar support services for scientific and exploration activities on the Moon.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:
Middle: Demonstrate extraction and processing of lunar resources to produce mission-enabling commodities such as oxygen and water in limited operational quantities. Demonstrate operational-scale surface communications and navigation networks. Enable entry of commercial provision of services for non-governmental customers.
Late: Demonstrate extraction and processing of lunar resources to produce feedstock materials for lunar manufacturing.

Priority: High

Rationale: Successful pilot plant scale demonstrations of local production of valuable commodities and communication/navigation services provide the essential proof of concept needed in the business model to establish the marketability of lunar commerce and provide essential knowledge needed to scaling up to full production and service networks levels. Because the risk involved in these demonstrations is still substantial, this objective may be fully funded by government, though possibly executed by industry. Alternatively, the objective may be met through government/private partnerships backed with government commitment to advanced purchases as an anchor tenant to encourage development of full-scale capability by industry. Multiple pilot plant demonstrations with different commercial partners or contractors encourage competition in operational phases.

Initiative A: Conduct the earliest possible pilot plant scale demonstration of lunar surface production of oxygen, water and other mission consumables, using durable technical approaches to raw material collection and processing. Identify and measure system performance metrics related to quality, reliability, and safety.
Initiative B: Conduct the earliest possible operational capability of commercially provided communication and navigation systems on the lunar surface.
Initiative C: Enable commercial/medical research on the lunar surface by facilitating access to infrastructure and support.
Initiative D: Facilitate lunar entertainment, tourism, and recreational activities.

Initiative E: Provide servicing of science instruments and infrastructure.
Initiative F: Encourage spin-in/spin-off technology applications (e.g., technology transfer office).

Objective Sust-A-5: Transition to Commerce II: Commercially provided lunar support services for scientific and exploration activities on the Moon.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:
Late: Initiate competitive, commercially provided extraction and processing of lunar resources to produce mission-enabling commodities such as oxygen and water in full operational quantities. Commercially provide operational surface communications and navigation networks. Commercially provide services for non-governmental customers.

Priority: High

Rationale: Successful transition of one or more product or service activity from government subsidy to competitive commercial operation will introduce efficiencies that reduce cost to the government and enable redirection of governmental funds to new scientific and exploration endeavors.

Initiative A: Government and other entities purchase lunar surface produced oxygen, water and other mission consumables from competitive commercial sources using industry standard performance metrics related to quality, reliability, and safety.
Initiative B: Government and other entities purchase communication and navigation systems services on the lunar surface from competitive commercial sources using industry standard performance metrics related to quality, reliability, and safety.
Initiative C: Commercial and medical research is conducted on the lunar surface using commercially provided infrastructure and support.
Initiative D: Private customers purchase lunar entertainment, tourism, and recreational activities from commercial sources.
Initiative E: Government and other entities purchase commercially provided servicing of science and other instruments and infrastructure.

Goal Sust-B: Enable and Support the Collaborative Expansion of Science and Exploration

Experience from the Hubble Space Telescope and numerous scientific investigations on the Shuttle and ISS show that human ability to repair and upgrade science instruments is scientifically beneficial and cost effective compared to building and deploying replacements for failed systems. Human presence should be expected to enhance and expand the breadth, complexity and reliability of scientific activity on the Moon. On the other hand, scientific investigations on the lunar surface identified elsewhere in this roadmap will directly contribute to the ability of humans to live on the moon by identifying resources and unraveling fundamentally how the lunar environment affects physical and living systems.

Human activity on the moon will therefore be dedicated in significant part to directing, conducting and supporting a variety of scientific investigations in complement to exploration activities involving discovering and exploiting resources and otherwise learning to live away from the Earth. Substantial fractions of the scientific investigations might be accomplished robotically, with varying degrees of necessary human tending. In recognizing these overlapping functions, *sustainable* human scientific and exploration activities must involve identifying and exploiting savings from sharing various resources including instrument development funding, transportation costs to and on the moon, and the infrastructure for lunar surface power, communications, process consumables, maintenance and repair.

Objective Sust-B-1: Implementation of comprehensive, coordinated integration of diverse scientific and exploration activities to maximize complementary operations and minimize operational and environmental conflicts.

Any single initiative of lunar activity, from an individual science instrument to the human outpost, undertaken alone is expensive, in may cases beyond any broadly-accepted estimate of the value returned, however large that value might be. Additionally, diverse lunar activities may conflict in fundamental ways, e.g. lunar atmosphere science and optical telescopes disturbed by dust raised by nearby crewed-rover operations. While there are solutions to terrestrial versions of these dilemmas including standardized energy, transportation and communications networks, and government planning and regulatory agencies, they were decades in the making and not applicable to the lunar environment. Lunar activities must be planned and conducted in such as way as to bring the cost of individual activities to sustainable levels through sharing of resources and standardized infrastructure, methodical reduction of technical and operational risks, and long-range interdisciplinary planning. The unprecedented challenge is to build these collaborative and regulatory systems before most of the activities begin and with international participation, both public and private.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:

Early: Identify, develop and deploy instrumentation systems that support early science objectives and early exploration technology demonstrations. Evolve and implement engineering standards for lunar systems and organizational structures to facilitate collaborative lunar activities.
Middle: Establish and conduct high level coordinated planning and operations to anticipate and prevent conflict between diverse lunar activities
Late: Transition control of planning and operations to direct participants

Priority: High (Early and Middle); Medium (Late)

Rationale: Comprehensive planning, including all relevant participants, can reduce development and operational costs and reduce the risk of operational conflict, thereby improving the value returned by lunar science and exploration activities. To be most effective, these planning systems must be in place before substantial lunar activity begins, thereby reducing costs and avoiding conflicts through anticipation rather than reaction.

Initiative A: Identify interdisciplinary array of science measurements and instruments that can be combined into mission scenarios and utilize standardized transportation, power, communication and other infrastructure systems.
Initiative B: Build roads, harden surfaces, build landing pads/berms, etc. to reduce dust generation due to activities around the Outpost/Settlement.
Initiative C: Develop technology standards for minimizing or eliminate purging and venting from suits, rovers, habitats, and landers.
Initiative D: Develop approaches to minimize landing/ascent plume exhaust deposition thru engine design, engine placement, and landing/ascent path trajectories.
Initiative E: Coordinate instrument measurement requirements against each other and lunar infrastructure (ex. radio telescope and communications spectrum and antenna location).

Objective Sust-B-2: Establishment and implementation of comprehensive site-selection criteria and processes.

The selection of sites for the emplacement of assets for scientific investigations or exploration activities is a rare occasion resulting in the commitment of substantial and possibly irreplaceable resources. The various parties interested in the properties of the selected site may have differing objectives for its collaborative use suggesting both a need for balanced negotiations and the best obtainable data from the candidate locations. In addition to considering the viewpoints of all partners, governmental, commercial, academic, and the international counterparts of each of these, practical operational considerations are crucial including transportation, communication and power availability, local resource availability and geological features amenable to well-protected human habitats.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:

Early: Identify, develop and deploy instrumentation systems that support robotic data collection from candidate sites serving early science objectives and early exploration technology demonstrations. Evolve and implement organizational structures to facilitate collaborative lunar outpost site selection processes.
Middle: Extend the site selection process to identify major science or exploration investigations located away from the human Outpost and robotically or human tended.

Priority: High (Early and Middle)

Rationale: Only one Outpost or Settlement site may be established on the Moon in the foreseeable future. Selecting an optimal site incorporating initial and long-term objectives of all interested parties is needed to ensure maximum productivity of benefit to Earth from science, exploration, and commerce.

Initiative A: Perform robotic precursors to evaluate terrain, minerals, resources, light/environment aspects and local items of science interest.
Initiative B: Establish an international board of government, industrial and academic participants to identify and manage site selection criteria, weighting factors and selection processes to evaluate potential sites for major collaborative lunar activities, including the lunar Outpost and Settlements.

Objective Sust-B-3: Development of surface power and energy storage systems.

Energy in useful forms is a fundamental prerequisite to any lunar activity, and the primary limitation to the growth of infrastructure capabilities. Anticipated lunar activities will require primarily electrical power, but many processes may utilize thermal energy directly obtained from the sun. Power systems must include efficient energy storage capability to meet peak power and substantial nocturnal demands, and must utilize renewable supplies of consumables. Renewable energy is directly tied to the development of in-situ resource utilization technologies for the production of energy system consumables. Efficient and low mass power distribution systems are needed as well as support for mobile operations and long distance transportation systems. Distributed power generation may be more efficient than long distance power transmission. Substantial heat rejection systems are required in the lunar environment. Power supply is a potential commercial enterprise. Sustainable lunar surface operations will depend on minimal dependence on terrestrial supplies of energy or energy infrastructure.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:
Early: Develop and deploy power systems compatible with mobile and distributed lunar surface assets, staying ahead of consumer demand. Establish power system standards compatible with the needs of the international science, exploration and commercial sectors.

Middle: Deploy substantial renewable power systems to support major science or exploration investigations located both at the human Outpost and at remote sites. Provide energy systems for human and robotic surface transportation.

Late: Deploy renewable power systems substantially manufactured using local materials and consumables to supply the energy needs of stationary, mobile and remote lunar activities.

Priority: High (Early and Middle); Medium (Late)

Rationale: Energy in useful forms is a fundamental prerequisite to any lunar activity. The growth in lunar energy supplies is perhaps the single most important pacing item in the growth of lunar activity.

Initiative A: Develop high-efficiency, low mass, solar photovoltaic systems.
Initiative B: Develop robust fuel cell technology compatible with the lunar environment.
Initiative C: Develop regenerative fuel cell technology compatible with the lunar environment.
Initiative D: Develop fuel cell reagent production capability.
Initiative E: Establish power system standards, including electrical, thermal and mechanical aspects.
Initiative F: Develop large-scale stationary and small-scale distributed (Thermal Wadi) thermal energy storage systems.
Initiative G: Develop in-situ fabrication and assembly of energy production and distribution (solar array fabrication).
Initiative H: Develop power beaming from orbit and between surface systems.
Initiative I: Develop reliable and safe nuclear power system.

Objective Sust-B-4: Establishment of sustainable transportation between Earth and the lunar surface.

The current NASA lunar transportation and operation architecture is based almost entirely on expendable vehicles including their propulsion, power, communication and other critical systems. At the same time, current human space activities in Earth orbit and early human activity on the moon will require substantial logistical supplies to keep the crew alive and systems running. Alternative transportation architectures that re-use or refuel assets more than once between Earth orbit and lunar orbit and between lunar orbit and the lunar surface could significantly reduce transportation costs for all lunar activity. Transportation systems are a possible commercial enterprise.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:

Early: Demonstrate the feasibility of ISRU produced fuel for ascent from the lunar surface to reduce non-productive landed mass. Ensure that expendable approaches used in early lunar transportation systems are upgradable to incorporate reusable features. Attempt commercial delivery of early robotic science instruments and exploration system demonstrations.

Middle: Establish sustainable transportation between Earth and the lunar surface including reusability, propellant depots and in-situ propellant production.

Late: Reduce or remove impediments to commercial supply of sustainable transportation systems

Priority: High (Early, Middle, and Late)

Rationale: Transportation costs are a major cost element of placing assets on the lunar surface. Reduction in these costs through reuse and refueling capabilities are an essential element of establishing sustainable lunar activity. Early demonstrations of commercial delivery could increase opportunities for scientific investigations and exploration technology demonstrations through reduced costs.

Initiative A: Utilize incentivized commercial transportation to deliver early science instruments.
Initiative B: Develop reusable in-space Earth to lunar orbit (or L1) transportation systems.
Initiative C: Develop reusable Lunar Orbit (or L1) to Surface lander/ascent transportation system.
Initiative D: Develop in-space and surface propellant depots and propellant transfer systems.
Initiative E: Develop lunar in-situ propellant production, and propellant transfer systems, including oxygen, methane, and/or hydrogen.
Initiative F: Develop robotic servicing of reusable transportation systems.

Objective Sust-B-5: Deployment of Robotic Facilities for Science and Exploration Operations.

Detailed expositions of valued scientific investigations that could be conducted on a potentially global scale on the moon are provided in other sections of this roadmap. It is clear that many of them would be sited in remote locations difficult, dangerous, or with no need for human tended operations. A significant portion of these investigations could be conducted before the human return to the moon in order to characterize the lunar environment undisturbed by human activity, and for other scientific reasons. Similarly, the development of technologies that are being prepared for human return and continued presence on the moon are challenged by the lack of sufficient technical data characterizing the lunar environment for engineering purposes, including the location of harvestable resources from the lunar soil and the response of physical systems and live organisms to the lunar gravity and radiation environment.

It is clear that there are advantages to human participation in many scientific investigations envisioned for lunar operations. These advantages include direct scientific observation and analysis, in-situ direction of investigations, and highly adaptable maintenance and repair functions. However, a timeline for efficient and sustainable science and exploration activities on the moon requires the implementation of early and continued robotic operations. The most important return from early, i.e. well before the human return, robotic missions will be engineering data, resource mapping, and technology demonstrations; all essential to reducing mass, power and design risk for human exploration activities. Benefit will increasingly accrue to a variety of science investigations in later periods.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:

Early: Define and execute robotic missions to selected lunar sites to conduct pristine lunar environment characterizations, resource mapping, engineering measurements, and technology demonstrations. Foster close collaboration between science and engineering objectives. Attempt commercial delivery of early robotic science instruments and exploration system demonstrations.

Middle: Establish robotic operations to conduct remote science investigations and support for human exploration operations.

Late: Reduce or remove impediments to commercial robotic operations

Priority: High (Early, Middle), Middle (Late)

Rationale: Characterization of the pristine lunar environment will be seriously hampered once human activity is established. Resource mapping data may strongly affect the site selection of the human outpost. Engineering measurements characterizing the behavior of key processes in the lunar environment and the demonstration of key technologies there will substantially reduce the mass, cost and risk of establishing a sustainable human presence. Early demonstrations of commercial robotic operations could increase opportunities for scientific investigations and exploration technology demonstrations through reduced costs. Performance of systems in reduced gravity is especially useful to feed forward applications on Mars and contributes to fundamental understanding applicable to terrestrial technology.

Initiative A: Develop standardized robotic platforms for lunar operations that reduce the unit cost of such platforms through amortization of development costs and economies of scale in manufacturing and delivery.

Initiative B: Utilize robotic precursor missions to conduct selected lunar science investigations that focus on characterizing the pristine lunar environment and contribute to identifying lunar resource concentrations.

Initiative C: Utilize robotic precursors to evaluate and obtain critical fundamental, applied, design, and engineering data for lunar infrastructure (ex. life support, power, ISRU, communications, etc.).

Initiative D: Coordinate ISS and lunar initiatives to maximize benefit of ISS to lunar science and exploration activity.

Initiative E: Develop standardized infrastructure on the lunar surface for support of robotic operations including power, communications, navigation and other systems.

Initiative F: Establish provisions and infrastructure (power, rack space, etc.) for experiments in government-supplied, tele-operated testing module (US and International) for future generations of lunar hardware and Feed Forward.

Initiative G: Utilize commercially provided module to support US and International experimenter research for future generations of lunar hardware and Feed Forward research.

Initiative H: Establish commercially provided module to support commercial research for Earth and Space applications.

Initiative I: Utilize infrastructure and long-term surface stay capabilities for life sciences research (e.g. bone loss, radiation exposure, dust, etc.).
Initiative J: Provide assembly services for complex science instruments (e.g., high-energy physics detectors).
Initiative K: Utilize in-situ produced materials and products to support and enhance laboratory evaluations.
Initiative L: Demonstrate and utilize surface preparation and construction equipment to emplace Earth supplied instruments.

<u>Objective Sust-B-6</u>: Establishment of Global Communications and Navigation Capability.

Communications capability to connect scientific investigations and human exploration activities with each other and with terrestrial partners must be conceived with the intention of expansion to global reach, and then grow at a pace sufficient to stay ahead of demand. Similarly, capability for global position determination and navigation is essential for mobile operations, precision landing and global transportation systems. A challenge to this essential aspect of sustainable lunar activity is developing these systems with not only sufficient geographical reach, but also sufficient bandwidth capacity to anticipate growth in data volume. Additionally, standardization of communication and navigation systems reduces the cost to individual users and facilitates system expansion. High definition imagery from the moon will play an essential role in engaging the public to participate in lunar science and exploration activity.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:
<u>Early</u>: Establish continuous communications capabilities between high value science and exploration sites and Earth with bandwidth sufficient to satisfy human operations. Establish technical approach to lunar surface navigation with experience from early robotic precursor missions.
<u>Middle:</u> Establish international communications and navigation standards for lunar activities with capacity for global reach. Attempt commercial provision of lunar communications and navigation systems.
<u>Late:</u> Reduce or remove impediments to commercial communications and navigation systems.

Priority: High (Early, Middle), Medium (Late)

Rationale: Communications and navigation systems fundamentally enable lunar activities of any kind. While dedicated systems provided by individual lunar activities might occur in early missions, the reduction in cost to lunar activities by shared or possibly commercially provided high-capacity communications and precise navigation systems will be an essential contribution to the sustainability of the lunar enterprise.

Initiative A: Establish interoperability and standards for communication, navigation, and surface reference.
Initiative B: Encourage a commercial or international-partner provided communications satellite to provide telemetry for early robotic missions (including far side) operations and increased capability for early human return.
Initiative C: Expand bandwidth for local and regional crew investigations and increased moon-Earth communications, including commercial entertainment, education, etc.
Initiative D: Establish global communications and navigation network.
Initiative E: Allow science instruments to utilize navigation (local and global) set up for crewed operations and long-range traverse activities.

Objective Sust-B-7: Establishment of sustainable human transportation between lunar sites.

At the pace that human lunar exploration and scientific investigation activities expand to substantial distances from the initial lunar Outpost, long-range surface transportation and transportation linkages between various lunar surface locations will be needed. In addition to the vehicles needed for long-distance transportation, power supplies, life support systems, communication networks, navigation systems, and other critical crew support capabilities will be needed. For early and middle term activities, long-range rovers, utilizing pre-positioned supplies of energy and life support consumables will suffice. In some instances, capable robotic rover assets may reduce crew transportation requirements. As the need for longer distance transportation grows, reusability and propellant production will be required.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:
Early: Utilize mobile robotic assets and long-range crewed rovers for limited surface transportation requirements.
Middle: Demonstrate capability for long-range transportation.
Late: Establish long-range transportation capability.

Priority: Low (Early), Medium (Middle), High (Late)

Rationale: If multiple human operations sites are established, then transportation between them will be essential.

Initiative A: Provide long-range robotic and pressurized rovers for distances of up to 100 kilometers.
Initiative B: Provide roads/pathways connecting sites of repeat visit around Outpost and elsewhere to minimize maintenance/wear.
Initiative C: Provide oases or way stations including resupply of energy, life support consumables, pressurized or unpressurized shelter, etc.
Initiative D: Provide hoppers, depending on the availability of ISRU propellants.

Objective Sust-B-8: Deployment of habitat and laboratory facilities for human science and exploration operations.

This objective includes all things needed for establishing human-habitable living and working quarters, and for the expansion of these capabilities from early, short duration missions through the establishment of a human exploration outpost and permanent self-sustaining settlements. In principle, the scope of this objective includes all major systems needed to sustain human activity including power, transportation, communications, habitat construction, life support, and crew health systems. However, major systems needed to support both human and robotic activities are described as separate discrete objectives in the sustainability theme, keeping only uniquely human habitation requirements here.

The purpose of this objective is an evolution of capabilities for a safe and healthy human population to conduct scientific and exploration activities on the moon. Specific elements addressed here are crew safety and health, habitation site preparations, habitat construction and certification, and support for the major categories of crew activities.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:
Early: Obtain detailed characterizations of potential lunar outpost sites that relate to the health and safety of the crew. Establish initial crew habitat for short duration missions including support of scientific investigations and exploration activities.
Middle: Demonstrate and deploy capability for long-term habitability of the moon including shirtsleeve environment and scientific laboratory capabilities
Late: Demonstrate and deploy capability for expanding human habitation capabilities using local materials, construction and certification

Priority: High (Early and Middle), Medium (Late)

Rationale: As value is identified for expanded human presence on the moon for scientific investigations, exploration objectives, and use of the moon for feed forward capabilities, habitation infrastructure requirements will grow for an expanding human population including individuals that remain longer and have substantial personal as well as professional needs.

Initiative A: Characterize aspects of the lunar environment that affect human health and safety including lunar regolith dust, radiation, temperatures, etc.
Initiative B: Develop reliable space weather prediction, monitoring, and mitigation technologies.
Initiative C: Develop long-term human health care and monitoring for lunar gravity conditions including any needed countermeasures, tele-medicine, monitoring devices and instruments, drugs, etc.
Initiative D: Develop and implement site preparation and emplacement civil engineering capabilities for roads, landing pads, protection berms, science instrument emplacement, nuclear reactor burial, etc.
Initiative E: Develop closed-loop life support systems compatible with ISRU derived consumables for loss makeup and expanded habitat capability.
Initiative F: Develop a high performance planetary mobility/EVA suit system to support multiple, distributed science and exploration activities.

Initiative G: Provide locally constructed radiation and micro-meteorite protection barriers including the use of regolith, water, hydrogen-based plastics, habitat burial, etc.
Initiative H: Define and Develop scientific laboratory capabilities, tailored to the lunar gravity environment, to conduct effective science activity in conjunction with advanced robotic operations and human science and exploration sorties.
Initiative I: Develop facilities to support human executed manufacturing and repair capabilities, tailored to the lunar gravity environment, to support a range of activities from scientific instruments to habitat construction.

Objective Sust-B-9: Establishment of in-situ production of life-support, power system reagents, propellants and related resources.

Production and recycling of mission consumables including oxygen, water, carbon-based fuels, and various laboratory gases are a key element of sustainably reducing the mass and cost risk associated with the logistical supply of materials brought from Earth. As these production capabilities grow, they enable and support the expansion of human and robotic activity through increased capacity of power production, transportation, life-support, and radiation-protection systems. Reliable production of mission consumables and the sustainable cost savings they represent might be among the most important contributions from the lunar experience to human and robotic exploration of Mars and elsewhere.

Substantial interaction is inherently required between systems that produce such consumables and the systems that use them, implying the need for substantial system engineering efforts early in the development of lunar surface systems. Additionally, early demonstrations of these capabilities are essential for them to be incorporated into the planning of science and exploration activities in a mission critical role. The urgency of early demonstrations is amplified by the necessity of affecting the design of early robotic and human systems that could be initiated well before the return of humans to the moon.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:
Early: Conduct demonstrations of oxygen production and storage from lunar regolith at the largest affordable scale of capacity. Conduct detailed system engineering of human and robotic systems on the moon incorporating realistic assumptions of oxygen and water production.
Middle: Demonstrate and utilize full-scale production of oxygen and water in sufficient capacities to meet life support, radiation-protection, and power system needs. Demonstrate production of carbon-based fuel using recycled waste.
Late: Utilize locally produced oxygen, water and fuel to eliminate logistics supply of consumables from Earth

Priority: High (Early and Middle), Medium (Late)

Rationale: Sustainable support for human and robotic scientific investigation and exploration activities depends on reducing the cost of operations. Production of mission consumables such as oxygen, water and carbon-based molecules as fuel will dramatically reduce the cost of logistical supply from Earth.

Initiative A: Demonstrate small-scale robotic production and storage of oxygen from reduction of lunar regolith.
Initiative B: Demonstrate hydrogen/water production techniques including extracting polar water/ice/volatiles in permanently shadowed craters, solar wind volatiles, trash processing, and propellant scavenging.
Initiative C: Develop multiple oxygen production from regolith techniques.
Initiative D: Develop and deploy full-scale production of life support consumables, including oxygen and water, fully integrated with life support systems.
Initiative E: Develop and deploy full-scale production of power system reagents fully integrated with surface power systems.
Initiative F: Develop carbon production or extraction techniques including solar wind volatiles, trash processing, and composite material processing.
Initiative G: Develop retrieval of other valuable atomic/molecular species through recycling of waste.
Initiative H: Develop and deploy production of carbon-based fuels from recycled waste streams.
Initiative I: Develop nitrogen and other gas species production techniques including solar wind volatiles, and trash/plastic processing.
Initiative J: Integrate the use of in-situ produced consumables by science instruments including fuel-cell reagents, purge gases, coolants, etc.

<u>Objective Sust-B-10</u>: Establishment of in-situ food production capability.

Sustainable support for increasing numbers of people on the lunar surface will require the local production of food supplies to reduce the cost of logistical resupply from Earth. Food production depends on substantial supplies of water, oxygen, carbon and nitrogen beyond other life-support and crew-protection needs and necessarily includes the complex recycling of waste. Food production involves plant growth eventually expanding into livestock husbandry. Reliable food production and the sustainable cost savings it represents might be among the most important contributions from the lunar experience to human and robotic exploration of Mars and elsewhere.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:
<u>Middle:</u> Demonstrate plant growth in lunar laboratories and gradually introduce locally grown produce into Outpost crew diet and waste recycling systems.
<u>Late:</u> Utilize locally produced food to eliminate logistics supply of consumables from Earth

Priority: High (Middle), Medium (Late)

Rationale: Sustainable support for human and robotic scientific investigation and exploration activities depends on reducing the cost of operations. Local production of food supplies will dramatically reduce the cost of logistical supply from Earth.

Initiative A: Develop plant growth capability linked to the lunar gravity and solar illumination environment and including regolith-as-soil, plant nutrient production and integration of plants into the atmosphere revitalization systems.
Initiative B: Develop livestock food production linked to the lunar gravity environment including the expanded life support system expansion needed for its implementation.

Objective Sust-B-11: Establishment of in-situ repair, fabrication, manufacturing and assembly capability.

Sustainable support for increasing diversity and complexity of assets on the lunar surface will require the local repair of equipment, manufacture of spare parts and the manufacturing and assembly of new equipment and instruments, all from local material feedstock. In-situ repair, fabrication and manufacturing will reduce the cost of logistical resupply from Earth. Food production depends on substantial capability to produce high-purity materials and shape and integrate parts into components of high quality and reliability, and necessarily includes the complex recycling of waste materials for reuse. In-situ repair, fabrication, manufacturing and assembly of equipment and instruments and the sustainable cost savings they represent might be among the most important contributions from the lunar experience to human and robotic exploration of Mars and elsewhere.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:
Early: Establish standards related to repair and spare parts manufacturing on the moon.
Middle: Demonstrate the production of high purity metals and semiconductor materials from lunar regolith. Demonstrate the manufacture of simple metal parts and photovoltaic cells and cell networks. Demonstrate maintenance and repair of science instruments
Late: Utilize local repair, fabrication, manufacturing, and assembly capabilities to eliminate logistics supply of parts from Earth

Priority: Medium (Early, Middle, and Late)

Rationale: Sustainable support for human and robotic scientific investigation and exploration activities depends on reducing the cost of operations. Local capability to repair equipment and instruments, manufacture spare parts and new equipment for local assembly will dramatically reduce the cost of logistical supply from Earth.

Initiative A: Establish standards for equipment and instrument design compatible with repairs in a lunar environment.

Initiative B: Establish standards for equipment and instrument design compatible with relaxed dimensional and material purity tolerances associated with parts manufacturing in a lunar environment.
Initiative C: Develop comprehensive tool kits for early human missions.
Initiative D: Demonstrate ability to repair or upgrade science instruments thru module swap-out.
Initiative E: Demonstrate ability to execute low-level repair of science instruments, such as soldering.
Initiative F: Identify the facility needs for a crew-supported habitable repair and upgrade facility that is incorporated into the crew living and working quarters.
Initiative G: Demonstrate manufacturing and assembly of parts using retrievable digital designs, including provisions for quality control.
Initiative H: Demonstrate and utilize surface preparation and construction equipment to support fabrication of part of scientific instruments, such as a radio telescope formed using a modified crater.

Objective Sust-B-12: Establishment of integrated design, development and testing capability.

Development and environmental testing costs for existing payloads sent in recent years to Mars are millions of dollars per kilogram. Sustainable scientific investigation and exploration of the moon requires that these costs be very substantially reduced through standardization, shared resources and subsystems, and the creation of infrastructure such as power, communications and surface transportation elements that offload these functions and the associated development costs from scientific and exploration payloads. Additional benefit is to be gained from the establishment of effective system of lessons learned from analog site testing, ISS and lunar surface precursor testing and results from scientific investigations in the lunar, physical and life sciences. Finally, a comprehensive capability for lunar environmental testing is needed to verify the function and reliability of components and systems bound for the moon.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:
Early: Establish standards related to interoperability of components and subsystems. Establish an international systems engineering convention for lunar systems to ensure that infrastructure elements are broadly useful to scientific, exploration and commercial users and providers. Identify and implement competitive lunar environmental testing capability
Middle: Implement the lunar surface infrastructure in accordance with the internationally accepted standards and conventions
Late: Adapt the lunar engineering standards to accommodate commercial innovation and evolving capability to produce instrumentation and other hardware using lunar resources

Priority: High (Early, Middle), Medium (Late)

Rationale: Sustainable support for human and robotic scientific investigation and exploration activities depends on reducing the cost of operations. Shared design standards, lessons learned, environmental testing, and lunar infrastructure will reduce the development and implementation costs of individual science investigation and exploration activities.

Initiative A: Develop international standards and interfaces.
Initiative B: Promote interoperability and commonality of designs through a collaborative systems engineering effort.
Initiative C: Conduct analog testing to demonstrate lunar capabilities and operations.
Initiative D: Conduct lunar environmental testing using terrestrial, ISS and lunar precursor facilities.
Initiative E: Utilize robotic and the initial human lunar missions to demonstrate infrastructure capabilities and technologies and retire risk early for lunar settlement.

<u>Goal Sust-C</u>: Enhance the Security, Peace and Safety of People on Earth

An aspect of the sustainability of lunar activity is the return of value to the people of Earth from missions other than scientific and exploration pursuits that cannot be accomplished in other ways. Uniqueness of the moon in this context stems from its position in space, its pristine environment and isolation from the Earth's environment.

<u>Objective Sust-C-1</u>: Detection and mitigation of threats from Near-Earth objects.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:
<u>Late:</u> Establish detection system on the lunar surface or on an orbiting platform in cis-lunar space to determine the flux of impacting material and identify potential impactors that may threaten the Earth and Moon.

Priority: High

Rationale: Collision of near-Earth objects such as asteroids can affect operations on the Moon and threaten human life on Earth.

Initiative A: Establish a detection system of impacts on the lunar surface to determine the flux of material to the lunar surface and in Earth-Moon space to better assess the magnitude of the impact hazard.

Initiative B: Expand the ground-based survey of near-Earth asteroids by using the lunar exploration architecture to produce a more complete catalogue of objects in near-Earth space that may pose a future impact threat.

<u>Objective Sust-C-2</u>: Beamed power and other lunar-based energy sources for terrestrial consumption.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:
<u>Late:</u> Utilize lunar materials to create an energy and power generating capability for consumption on Earth

Priority: High

Rationale: Sustainable support for human and robotic scientific investigation and exploration activities includes return of value to Earth. Substantial power can be harvested from space-based solar-sources and converted into forms that can be transferred to the Earth's surface. Space generated power can reduce carbon emissions and reduce dependence on energy from unreliable terrestrial sources.

Initiative A: Conduct detailed study to determine optimum site locations of solar-sourced power beaming capabilities, including sites that may be exploited in conjunction with lunar science and exploration such as the Earth-moon Lagrangian points.
Initiative B: Conduct detailed study of the technical feasibility and economics of supplying lunar produced propellants to Earth orbiting satellites.

Objective Sust-C-3: Remote and Hazardous Research and Testing.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:
Late: Utilize the remoteness and sterility of the lunar environment to establish capability to conduct high value but hazardous testing that cannot be contemplated on Earth.

Priority: Medium

Rationale: Sustainable support for human and robotic scientific investigation and exploration activities may include the return of value that may be derived from conducting hazardous research and testing on the moon. Such work would involve sufficiently large hazards to warrant the extreme isolation possible on the moon, such as extreme biological toxicity or infectious virulence.

Initiative A: Conduct detailed study to identify candidate hazardous testing needs and establish cost benefit analysis parameters.
Initiative B: Conduct detailed study to determine optimum site locations for hazardous testing facilities in conjunction with other human exploration site studies, including sites that may be exploited in conjunction with lunar science and exploration such as the Earth-moon Lagrangian points.

Objective Sust-C-4: Applied Earth observations.

Time Phasing:
Early: Establish the capability to conduct Earth observations on a hemi-spherical scale for purposes of practical applications such as dynamic weather, oceanic and forest/agricultural status.

Priority: Medium

Rationale: In conjunction with scientific observations of Earth, capabilities for data collection for real-time analysis of weather evolution, oceanic and vegetation and other dynamic systems on Earth can be observed on a hemispheric scale from the lunar surface. Observation systems may have extended longevity and opportunities for upgrading and maintenance by the intervention of human crew.

Initiative A: Conduct detailed study to determine optimum site locations of practical Earth observation capabilities, in conjunction with other human activity site studies, and including sites that may be exploited in conjunction with lunar science and exploration such as the Earth-moon Lagrangian points.

<u>Objective Sust-C-5</u>: Archiving of Critical Human Records and Biological Samples.

Time Phasing and Prioritization are the same for each Initiative.

Time Phasing:

<u>Early:</u> Establish a repository of human records including scientific, technological, historical, cultural, and other categories including not only non-volatile digital data, but also selected biological samples for preservation in case of catastrophic natural or human-induced disaster on Earth.

Priority: Medium

Rationale: The sterile and stable environment on the moon can be used as a repository of last resort for a compilation of human knowledge accessible to the survivors of extreme disaster on the earth.

Initiative A: Conduct detailed study to determine optimum site locations for a massive data and biological sample repository, including sites that may be exploited in conjunction with lunar science and exploration such as the Earth-moon Lagrangian points.
Initiative B: Conduct detailed study to estimate the volume of data and sample storage appropriate to such a repository.