The Lunar Exploration Roadmap.
Exploring the Moon in the 21st Century: Themes, Goals, Objectives, Investigations, and Priorities, 2009

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

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Introduction

The Lunar Exploration Roadmap Version 1.0 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 1.0 should **not** be considered as final. The full version 1.0 and companion spreadsheet are available from **http://www.lpi.usra.edu/leag/ler_draft.shtml**.

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. The Sustainability Theme is at the lowest fidelity, representing a small (but growing) body of opinion, and will require refinements, which will begin at the 2009 LEAG Annual Meeting.

Overall the roadmap is intended to layout an *integrated* and *sustainable plan* for lunar exploration that would 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 would enable commercial development, through early identification of "commercial on ramps", that would create wealth and jobs to offset the initial taxpayer investment. In addition, the roadmap would, 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 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. The themes are summarized here.

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

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).

FEED FORWARD (FF) THEME: **Use the Moon to prepare for potential 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 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 two Goals under this theme. One addresses hardware (Goal FF-A with 9 Objectives and 38 Investigations) and the other operations (Goal FF-B with 3 Objectives and 13 Investigations.

SUSTAINABILITY (Sust) THEME: **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. Return of value is an individual judgment and might include diverse factors as

scientific discovery, technology developments, 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.

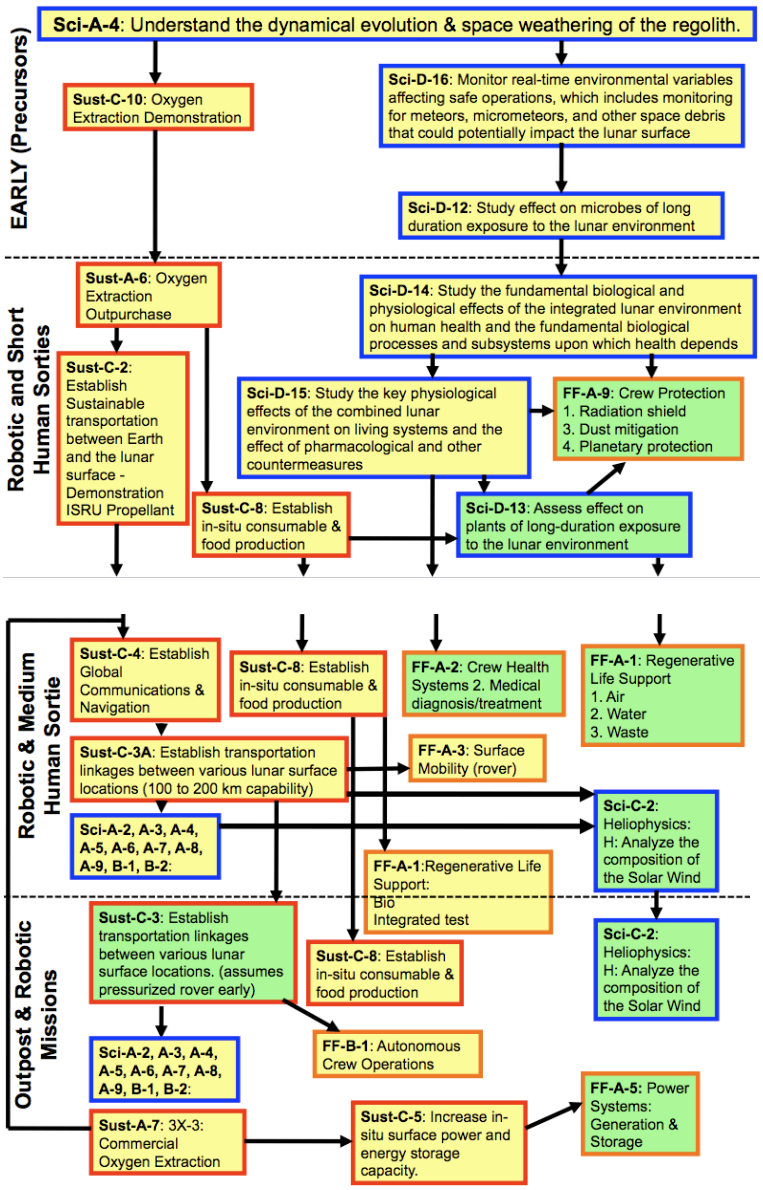

Figure 1: An example of roadmapping between Objectives. Blue outline = Science Theme; Orange outline = Feed Forward theme; Red outline = Sustainability theme; Yellow fill = High Priority; Green fill = medium priority.

Next, the time phasings and prioritizations are used to create the roadmap (in the companion Excel spreadsheet: **http://www.lpi.usra.edu/leag/ler_draft.shtml**).

Time Phasing Criteria

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.

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 include 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 Would best be 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 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 & 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, & 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 potential future missions to Mars and other destinations.
GOAL FF-A: 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 would 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 that would 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 would 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).

GOAL FF-B: Use the Moon as a test-bed for missions operations and exploration techniques to reduce the risks and increase the productivity of potential 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).

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

GOAL Sust-A: 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);

GOAL Sust-B: 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).

GOAL Sust-C: 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 & Hazardous Research & Testing (2 Initiatives);

Objective Sust-C-4: Applied Earth observations (1 Initiative);

Objective Sust-C-5: Archiving of Critical Human Records & Biological Samples (2 Initiatives).