THE OPEN GATEWAY: LUNAR EXPLORATION IN 2050. S. Lawrence[1], C. Neal[2] and the LEAG Executive Committee. [1]ARES, NASA Lyndon B. Johnson Space Center, Houston TX 77058, USA (samuel.j.lawrence@nasa.gov) [2]Dept. Civil & Env. Eng. & Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, USA (neal.1@nd.edu)

Introduction: The Moon, with its fundamental science questions and abundant, potentially useful resources, is the most viable destination for near-term future human and robotic exploration. Given what we have learned since Apollo, the lunar frontier now presents an entirely new paradigm for planetary exploration.

The Lunar Exploration Roadmap [1], which was jointly developed by engineers, planetary scientists, commercial entities, and policymakers, is the cohesive strategic plan for using the Moon and its resources to enable the exploration of all other destinations within the Solar system by leveraging incremental, affordable investments in cislunar infrastructure. Here, we summarize the Lunar Exploration Roadmap, and describe the immense benefits that will arise from its successful implementation.

The **Lunar Exploration Roadmap** presents a sustainable strategy to make concrete advances along three themes.

Science – *Use the Moon for scientific research that addresses fundamental questions about the Moon, the Solar System, and the universe around us:* The Moon is an evolved planet in its own right – having a crust, a mantle, and core – and therefore the most accessible destination to cohesively address planetary science questions. The Moon retains a record of the formation, evolution, and impact history of Earth and the other inner solar system planets, as well as an otherwise inaccessible record of the Sun's evolution and history. There are over four decades of planetary science hypotheses that lunar geologic fieldwork will address.

The lunar surface also provides a unique and stable long-term platform for astronomy; in particular, human-tended radio observatories on the far side or optical interferometers could produce dramatic advances in astrophysics.

Sustainability – *Use the Moon to learn how to live and work productively off-planet, for increasing periods, enabling human settlement:* The Moon has abundant material and energy resources that can be used to decrease the costs and dramatically increase the capabilities of future Solar System exploration. Lunar resources, in particular, offer an enduring opportunity for commercial investment and bringing cislunar space fully into Earth's economic sphere while building international partnerships. Commerce is a key aspect of ensuring the sustainability of future space activity. Public-private partnerships, growing from initial government investment, will sustain infrastructure and create new spaceflight capabilities. The establishment of a lunar outpost is the most feasible method of establishing an economic anchor in cislunar space, similar as to how the International Space Station has spurred low-Earth orbit transportation.

Feed forward – *Use the Moon to prepare for future missions to other destinations:* The Moon is the only viable deep-space test-bed for testing technologies, systems, and operations to enable cost-effective human operations beyond low-Earth orbit. The Moon's combination of radiation, hard vacuum, and low-gravity provide a unique laboratory to study the physiological, biological, and biomedical aspects of long-duration operation on planetary surfaces. Irrespective of the well-established ways in which lunar exploration is required for the success of future voyages to Mars and beyond, the establishing a lunar outpost will help to establish the comprehensive industrial base required to successfully make voyages to Mars and beyond.

Time Phasing: Each of the three themes in the LER have been developed with time phasing in mind, and the engineering aspects have been defined by LEAG as occurring:

Early: Robotic precursors and up to the 2nd human landing (< 1 lunar day),

Middle: Initial outpost build-up to including says of 1 lunar day and part of the lunar night, including robotic support missions; and

Late: Activities associated with and following the establishment of the lunar outpost.

For scientific goals, LEAG has incorporated the NRC Scientific Context for the Exploration of the Moon report [2] findings for the prioritization of science concepts and goals that were specifically studied in that report. We have also included, through consultation with leaders in various science related communities, how science related to Earth Observation, Heliophysics, and Astrophysics could be achieved from the Moon.

Technologies: Building cislunar infrastructure does not require technologies wildly outside our experience base; rather, it is facilitated with evolved versions of currently existing technologies such as microwave power transmission, laser communications, solar power, regenerative life support, propellant storage, and telerobotics. In terms of new investments, the demonstration and flight qualification of presently well-conceptualized (but unflown) technologies for cislunar in-situ resource extraction and utilization would provide a capability required for any future sustained human space operations.

Vision for Lunar Exploration in 2050: Successfully implementing the Lunar Exploration Roadmap will result in a variety of benefits for planetary science and exploration. While predicting events three decades hence is fraught with uncertainty, following the Roadmap will produce a dramatically altered landscape for planetary science and exploration by the year 2050. The proximity of the Moon to the Earth offers intriguing possibilities for a future where lunar surface operations are commonplace, with at least several hundred people living and working on the Moon. Examples of the kinds of activities we foresee include:

Transformational Planetary Science: Geology is a field science, and can best be done by humans, mapping and solving complex field problems to answer fundamental science questions. By the 2050s, we anticipate that in-person fieldwork would be undertaken by academic institutions (much like NASA and NSF support activities in Antarctica) yielding profound benefits for our understanding of the Solar System. A lunar outpost, for example, could enable lengthy expeditions to geology field sites across the lunar surface using both humans and human-tended robots, depending on the science question to be addressed.

Enduring Commercial Markets: Fueled by access to lunar resources, large-scale operations on the surface of the Moon and in cislunar space are commonplace, and have expanded Earth's economic reach and dramatically increased the human presence in cislunar space. From refueling assets in geosynchronous space to tourism to space-based solar-power, commercial activities in cislunar space are routine and profitable.

A New Paradigm: Cislunar infrastructure, powered by lunar resources, promises a dramatic increase in capability for NASA generally and planetary science specifically. Missions could be assembled at L2 and supplied using lunar resources, dramatically lessening current mass constraints, prior to routine departures to Mars and other destinations. As another example, returned samples requiring complete isolation from Earth's biosphere from other destinations (such as Mars, or outer planet moons) could be received and examined at completely isolated facilities on the lunar surface.

Implementation Strategy: There are near-term steps that must be undertaken to ensure that the breathtaking potential of lunar exploration is realized.

LEAG has developed a Roadmap implementation [3] strategy for the 2020s designed from the outset to advance science and have viable on-ramps for commercial activity with measurement objectives clearly traceable to the Strategic Knowledge Gaps [4].

Phase 1 – Prospect for Resources: Build upon the results of recent lunar missions to define if the resources are actually reserves. Such prospecting needs to: define the composition, form, and extent of the resources; characterize the environment in which the resources are found; define the accessibility of the resource; quantify the geotechnical properties of the regolith in which the resources reside; establish the capability to autonomously traverse several tens of kilometers to sample to determine the lateral and vertical resource distribution on meter scales; identify resource-rich areas for targeting future missions; and establish capabilities such as automated ***cryogenic*** sample return and curation to facilitate the assay of potential resources.

Phase 2 – Demonstrate ISRU: Based on the results of Phase 1, the next step would be to carry out an end-to-end demonstration of resource extraction and utilization, which addresses important science questions, validates key technologies, including feedstock acquisition and handling, resource storage, ISRU system longevity, and dust mitigation strategies.

Phase 3 – Lunar Resource Production: Based upon the results of Phase II, begin to utilize lunar resources to enable increasingly complex operations on the surface, including life support for human outposts and propellant for reusable landers, as part of a sustainable human-tended facility on the surface [e.g., 5]

Conclusions: The Moon is the natural "Gateway to the Solar System", representing the fundamental underpinnings for understanding Solar System processes and history. The Moon is also the critical enabling asset for any human exploration activity that the world may undertake in space, now and in the future. Lunar exploration enables an approach to Solar System exploration that involves a series of logical, incremental steps, producing mutually reinforcing capabilities that enable sustainable planetary science, exploration, and commerce. By the 2050s, creating the capabilities inherent in executing the Lunar Exploration Roadmap will enable us to go anywhere, and do things heretofore only imagined, throughout the Solar System – with clear benefits for planetary science.

References: [1] LEAG (2011). The Lunar Exploration Roadmap: Exploring the Moon in the 21st Century [2] NRC (2007) Scientific Context for the Exploration of the Moon [3] Shearer, C. K. et al. (2011) LEAG Robotic Campaign Analysis. [4] Shearer, C. K. et al. (2016), 2016 Annual LEAG Meeting, Abstract 5025. [5] Spudis P. & Lavoie A. (2011) AIAA SPACE 2011 Conference & Exposition, Long Beach, CA, 24 pp. AIAA-2011-7185.