THE LUNAR EXPLORATION ROADMAP: A PROGRESS REPORT FROM THE LUNAR EXPLORATION ANALYSIS GROUP (LEAG). C.R. Neal, Department of Civil Engineering & Geological Sciences, University of Notre Dame, Notre Dame, IN, 46556, neal.1@nd.edu

The Lunar Exploration Roadmap (LER) is being developed by LEAG for NASA as a community effort in order to outline the major science and exploration goals that need to be reached and/or are desired in order that our return to the Moon is sustainable and long term. The effort is being lead by a number of Specific Action Teams (SATs) that are developing Objectives and Investigations from Themes and Goals that were derived from President Bush's speech in 2004 [1], the Global Exploration Strategy [2], the NRC Decadal Survey [3], and the NRC Report on the Scientific Context for the Exploration of the Moon [4].

The LER contains three Themes: the Science Theme (***Pursue scientific activities to address fundamental questions about the solar system, the universe, and our place in them***); the Feed Forward Theme (***Use the Moon to prepare for future missions to Mars and other destinations***); and the Sustainability Theme (***Extend sustained human presence to the Moon to enable eventual settlement***). Within each theme are a number of goals and objectives. Some themes are developed to the point of proposing investigations. Community advice was and is being sought for guidance on all tiers of the roadmap via web input using a web site hosted at the Lunar and Planetary Institute. Full details of the Lunar Exloration Roadmap can be found at http://www.lpi.usra.edu/surveys/LER/ with a username of "leag" and a password of "moonorbust".

Science (Sci) Theme: contains 4 goals: (A) *Understand the formation, evolution, and current state of the Moon*; (B) *Use the Moon as a "witness plate" for solar system evolution*; (C) *Use the Moon as a platform for astrophysical, heliophysical, and earth-observing studies*; and (D) *Use the unique lunar environment as a research tool*. The flow of the Science themes & goals to objectives & investigations is in Table 1.

Feed Forward (FF) Theme: contains two Goals: (A) *Identify & test technologies and systems on the Moon to enable robotic & human solar system science and exploration*. This goal contains 9 Objectives with 38 investigations; (B) *Use the Moon as a test-bed for mission operations and exploration techniques to reduce the risks and increase the productivity of future missions to Mars and beyond*. This objective contains two objctives with 10 investigations (see Table 2).

Table 2: Theme FF Objectives

A-1 Develop surface life support systems to reduce risks of long duration Martian surface stays (7 Investigations).
A-2 Develop Crew Health Systems That Enable Safe, Long Duration, Surface Stays (4 Investigations).
A-3 Develop surface mobility capabilities for Lunar and Martian surface exploration (3 Investigations).
A-4 Develop the capability to acquire and use local resources to sustain long-term exploration and habitation (5 Investigations).
A-5 Develop the capability to produce power on planetary surfaces to allow humans to work and live productively (4 Investigations).
A-6 Develop the capability to autonomously land safely and accurately on the Moon and Mars (3 Investigations).
A-7 Develop the capability to autonomously land safely and accurately on the Moon and Mars (2 Investigations).
A-8 Develop the capability for crews to communicate with surface assets, and navigate to/from them (5 Investigations).
A-9 Allow human crews to operate safely on planetary surfaces, protected from the environmental hazards (5 Investigations).
B-1 Develop the capability for autonomous crew operations on the Moon and Mars (5 Investigations).
B-2 Develop productive, efficient human-robotic interaction for planetary surface exploration (5 Investigations).

Sustainability (Sust) Theme: The theme contains 5 goals: (A) *Expand Science: Provide support, services, and infrastructure to enhance and enable new science to the Moon, on the Moon, and from the Moon* (crossover with Sci Theme); (B) *Expand Human Exploration: Expand in-space and surface transportation capabilities beyond initial NASA transportation architecture to discover and reach new territories* (crossover with Sic and FF Themes); (C) *Enhance Security: Protect and benefit Earth, and guarantee peace and safety both for settlers and for the home planet*; (D) *Commercial on ramps* (Enable space economic activity to benefit Earth and lunar settlement and to enable NASA to explore beyond the Moon); and (E) *Sustaining human presence on the Moon*. Goal Sust A contains 5 Objectives, Goal Sust B contains 7 Objectives, Goal Sust C contains 6 Objectives, Goal Sust D contains 3 Objectives, and Goal Sust E contains 5 Objectives. Thus far, a total of 42 Investigations have been developed, although not all objectives have had investigations developed under them. Importantly, the Sustainability Theme identifies on ramps for commercial companies to become involved in the long term plan for lunar exploraion. This is critical as having planned commercial on-ramps in the roadmap will allow NASA to transition to Mars without abandoning the infrastructure it has built up at the Moon.

References: [1] Bush G.W. (2004) A renewed Spirit of Discovery. www.whitehouse.gov/space/renewed_spirit.html [2] Global Exploration Strategy: The Framework for Coordination (2007) www.nasa.gov/pdf/178109main_ges_framework.pdf. [3] NRC (2003) New Frontiers in Solar System Exploration. NAP, Washington DC, 248 pp. [4] NRC (2007) The Scientific Context for Exploration of the Moon. NAP, Washington D.C. 112 pp.

GOALS	OBJECTIVES	INVESTIGATIONS
Understand the formation, evolution, and current state of the Moon.	Understand lunar differentiation	Inventory, relationships, and ages of nonmare rocks
		Inventory, relationships, and ages of mare volcanics and related intrusive rocks
		Determine the composition, structure, and variability of the crust
		Determine the composition, structure, and variability of the mantle
		Determine size and composition of the core
	Understand formation of the Earth-Moon system	Determine the bulk composition of the crust
		Determine the bulk composition of the mantle
		Determine the early thermal history of the Moon
	Understand volcanic processes	Determine how magma is generated and transported to the surface
		Determine how lava flows are emplaced on the Moon
		Determine the physical characteristics of pyroclastic deposits and vents
		Assessment of the volatiles driving lunar volcanic eruptions
	Understand the impact process	Determine and understand the stages of formation of simple and complex craters, and multi-ring basins
		Determine how impacts modify, redistribute, and mix materials
		Determine the origin and evolution of basin melt sheets
		Assess the possibility of impact-triggered magmatism
		Determine the production and evolution of the megaregolith
	Determine the stratigraphy, structure, and geological history of the Moon	Understand the impact history of the Moon
		Determine the stratigraphy of the lunar maria
		Determine the stratigraphy of the lunar highlands
		Determine the tectonic history of the lunar crust
	Understand the dynamical evolution and space weathering of the regolith	Characterize the structure and layering of the regolith, including the interface with underlying bedrock
		Determine the compositional variability of the regolith and how it relates to underlying rock
		Characterize the lunar regolith to understand space weathering processes in different crustal environments
		Characterize volatile concentrations and transport mechanisms
	Characterize the environment and processes in lunar polar regions	Map and characterize polar cold traps
		Map and characterize quasi-permanently illuminated areas
		Determine bedrock geology of polar regions
		Understand volatile sources and mechanisms of transport and deposition
	Development and implementation of sample return technologies and protocols	Develop a sampling strategy for the Moon
		Understand the scientific requirements for sample curation, packaging, and transport to Earth.
		Understand what analyses (field and laboratory) need to be done on the Moon to aid field studies and optimize the value of samples returned to Earth
		Enhance curatorial facilities on Earth to handle environmnentally-sensitive samples (e.g., ices)
	Understand the environmental impacts of lunar exploration	Determine baseline lunar environment
		Determine how the environment changes after the return of humans to the Moon
Use the Moon as a "witness plate" for solar system evolution	Understand the impact history of the inner Solar System as recorded on the Moon	Determine the impact flux during the basin-forming epoch
		Determine the impact flux throughout the post-basin-forming epoch
		Determine the composition and source of impactors
		Characterize the impact hazard to the Earth-Moon system
	Regolith as a recorder of extra-lunar processes	Characterize volatile concentrations and their variability
		Assess temporal variations in the Sun through studies of solar wind and solar flare products in the regolith
		Assess variability in the solar constant through detailed, long-term heat flow measurements
		Assess variations in cosmic radiation through time
		Search for meteoritic material (including terrestrial debris) in the regolith
Use the Moon as a platform for astrophysical, heliophysical, and earth-observing studies	Astrophysical Investigations using the Moon	Viewing the Universe and the Seeds of Galaxy Structure in the "Dark Ages"
		Probing the Universe at the Highest Energies
		Key Tests of the Strong Equivalence Principle in Gravitational Field Theory
		Site Characterization
		"Piggyback" missions to surface and lunar orbit (MOOs)
		Large Telescope at Earth-Sun L2
		Lunar Optical Interferometer
		Detect gravitational waves.
		Large Lunar Optical Telescope
		Search of exotic stable states of matter
	Heliophysical Investigations using the Moon	Near-Lunar Electromagnetic and Plasma Environment
		The Moon's Remnant Crustal Magnetic Fields
		Magnetotail Dynamics at Lunar Orbit
		Dust-Plasma Interaction on the Surface & Exosphere of the Moon
		Imaging the Heliopsheric Boundary
		Low-Frequency Solar Radio Astronomy
		Imaging Geospace from the Moon
		Analyze the composition of the Solar Wind
		High-Energy Optical Solar Observatory
		Sun's Role in Climate Change
		Understand and Predict Space Weather Impact on Robotic and Human productivity
		Characterize Radiation Bombardment on the Lunar Surface
	Earth Science Investigations using the Moon	Lightning distribution and frequency
		Variability of Earth's Top-of-Atmosphere
		Earth Albedo Variability
		Earth Land Surface Monitoring
		Infrared Observations of Earth
		Radar Interferometry of Earth
Use the unique lunar environment as a research tool	Investigate and characterize the fundamental interactions of combustion and buoyant convection in lunar gravity.	Investigate flame structure and instabilities near combustion limits, as defined by dilution, stoichiometry, temperature (low-temperature flames), etc.
		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
		Examine relatively large, lean weakly buoyant flames in hydrogen and methane in lunar gravity.
		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
	Perform tests to understand and possibly discover new regimes of combustion	Investigate new regimes of combustion, such as flame balls, which have been proposed as the mechanism for sustaining flames at very lean limits in earth gravity
		Investigate rarefied gas combustion, either as premixed flames or diffusion flames
		How does an unreacted hydrogen-oxygen mixture or even an existing flame react to exposure to naturally occurring, intense radiation, not filtered by an atmosphere?
		How does a large premixed reactive mixture, or a large flame, behave when exiting to a vacuum or to very low atmospheric pressure?
	Investigate interactions of multiphase combustion processes and convection at lunar gravity	Investigate the interaction of water mist with diffusion flames in lunar gravity
		Investigate the process of soot formation in lunar gravity.
		How is smoldering affected by low-g? How is flame spread over thick solid fuels affected?
	Obtain experimental data to anchor multiphase flow models in partial gravity environment	Test simple two-phase flow through straight channels at different inclinations under partial gravity
		Test two-phase flow through porous media/packed beds under partial gravity
		Assess efficacy of boiling heat transfer under lunar gravity
	Study interfacial flow with and without temperature variation to anchor theoretical/numerical models	Study low-Reynolds-number dynamic wetting in the presence of temperature gradients typical of the lunar environment and lunar gravity
		Validate relative importance of capillary-driven versus buoyancy-driven flow in various geometries
		Study the behavior of liquid wicking under lunar gravity
	Study behavior of granular media in the lunar environment	Obtain experimental data on gravity-driven, dense granular flows, such as flows out of a hopper, corresponding to Earth-based design methods
		Investigate impact of accumulated lunar dust on exposed radiative and optical surfaces
		Perform experiments examining possible strategies for dust management
	Investigate precipitation behavior in supercritical water in partial gravity	Measure salt deposition rate on heated surface in supercritical water-salt solutions with and without flow
		Assess effects of Lewis number on homogeneous and heterogeneous salt precipitation in supercritical water-salt solutions
	Investigate the production of oxygen from lunar regolith in lunar gravity	Study separation behavior within melt of solids and bubbles during oxygen production using lunar magma electrolysis
		Assess long-term performance and similarity of oxygen production employing ilmenite reduction techniques using fluidized beds
	Investigate the behavior of liquid-phase sintering under lunar gravity	Study the effect of solid volume fraction and varying operating conditions on liquid-phase sintering carried out on the lunar surface
	Study the fundamental biological and physiological effects of the integrated lunar environment on human health	Conduct fundamental research to understand the physiological, biological, and mental effects of the lunar environment on humans
	Study the key physiological effects of the combined lunar environment on living	Evaluate the impact of the combined lunar environment with and without the use of pharmacological countermeasures on cellular oxidative damage
		Evaluate the impact of the combined lunar environment with and without the use of pharmacological countermeasures on bone loss
	Evaluate consequences of long-duration exposure to lunar gravity on the human	Measure muscle atrophy resulting from long-duration exposure to 1/6 ge with and without supplemental exercise
		Measure bone loss resulting from long-duration exposure to 1/6 ge with and without supplemental exercise
	Understand the impact of Lunar environments on multiple generations of terrestrial life forms that impact human	Investigate the fidelity of replication of human microbial flora for variants, increase in virulence, and development of antibiotic resistance over thousands of generations
		Investigate the propagation of food sources/crops for multiple generations and nutritional value
	Monitor real-time environmental variables affecting safe operations	Establish a lunar environmental monitoring station to measure environmental variables
		Provide real-time environmental information relevant to daily lunar operations